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Development of Envelope Curves for Predicting Void Dimensions from Overturned Trees

Bryant A. Robbins, Johannes L. Wibowo, Kevin S. Holden,
and Maureen K. Corcoran

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Development of Envelope Curves for Predicting Void Dimensions from Overturned Trees

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Abstract

To evaluate the potential influence of a tree on embankment stability, it is necessary to estimate the void that will occur in the embankment if the root system were to fail from storm loads. Currently, there is no published scientific literature focusing solely on this issue from an engineering perspective. This study reviewed existing research regarding windthrow pit dimensions for the purpose of developing a data set to estimate void dimensions. Twelve studies from which data regarding void dimensions could be obtained were found, resulting in a total of 676 data points. From these data, relationships that predict windthrow pit diameter and depth as a function of tree diameter were developed.

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Contents

Abstract	ii
Figures and Tables.....	v
Preface.....	vii
Unit Conversion Factors	viii
1 Introduction.....	1
1.1 Background.....	1
1.2 Objective.....	1
2 Overview of Tree Uprooting.....	2
2.1 Terminology.....	2
2.2 Mechanics of windthrow.....	4
2.3 Factors influencing windthrow potential.....	5
3 Methods of Estimating Root and Pit Dimensions	7
3.1 Crown width	7
3.2 Tree height.....	7
3.3 Tree diameter.....	9
4 Previous Studies.....	12
4.1 Distribution and characteristics of windthrow microtopography on the Cumberland Plateau of Kentucky (Cremeans and Kalisz 1988)	12
4.2 Microsite variation and soil dynamics within newly created treefall pits and mounds (Peterson et al. 1990)	12
4.3 Catastrophic windthrow in the southern Appalachians: characteristics of pits and mounds and initial vegetation responses (Clinton and Baker 2000)	14
4.4 Damage and recovery of tree species after two different tornadoes in the same old-growth forest: A comparison of infrequent wind disturbances (Peterson 2000).....	16
4.5 Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns (Peterson 2007).....	17
4.6 Salvage logging after windthrow alters microsite diversity, abundance, and environment, but not vegetation (Peterson and Leach 2008)	17
4.7 Pedologic and geomorphic impacts of a tornado blowdown event in a mixed pine-hardwood forest (Phillips et al. 2008)	19
4.8 Modeling the anchorage of shallow-rooted trees (Achim and Nicoll 2009)	21
4.9 Sediment transport due to tree root throw: integrating tree population dynamics, wildfire, and geomorphic response (Gallaway et al. 2009).....	22
4.10 Estimating soil turnover rate from tree uprooting during hurricanes in Puerto Rico (Lenart et al. 2010)	23
4.11 The influence of windthrow microsites on tree regeneration in a mountain old growth forest (Simon 2010)	25

4.12	Effects of uprooting tree [sic] on herbaceous species diversity, woody species regeneration status, and soil physical characteristics in a temperate mixed forest of Iran (Kooch et al. 2012)	26
4.13	Other studies in the literature.....	27
5	Data Analysis	29
5.1	Windthrow pit diameter	29
5.1.1	Area to equivalent circular diameter	29
5.1.2	Pit width and length to equivalent circular diameter.....	29
5.1.3	Comparison and analysis of pit diameter data	31
5.2	Windthrow pit depth	36
6	Other Factors	40
7	Summary.....	43
8	Recommendations.....	45
9	Acknowledgements.....	vii
	References	47
Report Documentation Page		

Figures and Tables

Figures

Figure 1. Schematic of tree overturning (Schaetzl 1989b, reprinted with permission).	3
Figure 2. Force diagram of tree windthrow event (adapted from Achim and Nicoll 2009, used with permission).	4
Figure 3. Crown - root relationship (adapted from Smith 1964).	8
Figure 4. Root spread as a function of tree height (adapted from Day et al. 2010).	8
Figure 5. Relationship between tree diameter and windthrow pit volume (adapted from Putz 1983).	10
Figure 6. Linear regression of data adapted from Putz (1983) [triangles] and Lenart et al. (2010) [circles].	11
Figure 7. Tree DBH versus area of ground disturbed (adapted from Cremeans and Kalisz [1988]).	13
Figure 8. Windthrow pit size data (adapted from Peterson et al. [1990]); (A) pit width and (B) pit length as a function of tree diameter at breast height (DBH).	14
Figure 9. Windthrow pit and mound dimensions (adapted from Clinton and Baker [2000]).	15
Figure 10. Windthrow pit dimensions for Tionesta Scenic and Research Natural Area (adapted from Peterson [2000]).	16
Figure 11. Data for tornado blowdown site titled 'Taylor' in Peterson (2007): (A) pit length, (B) pit width, and (C) pit area.	18
Figure 12. (A) Pit area and (B) corresponding mound area from Peterson and Leach (2008) and Leach (2003).	19
Figure 13. Windthrow root wad dimensions (adapted from Phillips et al. 2008): (A) mean root wad depth, (B) surface area of uprooted soil mass, and (C) volume of uprooted soil mass as a function of tree DBH.	20
Figure 14. Tree DBH versus lateral root-plate diameter data (adapted from Achim and Nicoll 2009).	22
Figure 15. Root-plate volume data (adapted from Gallaway et al. 2009).	23
Figure 16. (A) Mound area and (B) mound volume as a function of trunk area (adapted from Lenart et al. 2010).	24
Figure 17. Windthrow pit dimensions from Simon (2010).	25
Figure 18. Illustration of equivalent circular diameter.	30
Figure 19. Original and equivalent circular data using pit dimensions and DBH from Peterson (1990).	31
Figure 20. Comparison of pit diameter data.	32
Figure 21. All data collected regarding diameter of windthrow pits.	33
Figure 22. Comparison of Achim and Nicoll (2009) to other data.	33
Figure 23. Windthrow pit diameter data excluding Achim and Nicoll (2009).	34
Figure 24. Regression of windthrow diameter data and 95% confidence intervals.	35

Tables

Table 1. Comparison of Puerto Rico and Panama data (Lenart et al. 2010).	11
Table 2. Summary of study by Cremeans and Kalisz (1988).....	13
Table 3. Summary of study by Peterson et al. (1990).....	14
Table 4. Summary of study by Clinton and Baker (2000).	15
Table 5. Summary of study by Peterson (2000).	17
Table 6. Summary of study specifics for ‘Taylor’ site in Peterson (2007).....	18
Table 7. Summary of study by Leach (2003) and Peterson and Leach (2008).	19
Table 8. Summary of study by Phillips et al. (2008).....	21
Table 9. Summary of study by Achim and Nicoll (2009).....	22
Table 10. Summary of study by Gallaway et al. (2009).	23
Table 11. Summary of study by Lenart et al. (2010).....	24
Table 12. Summary of study by Simon (2010).	26
Table 13. Pit and tree measurements from Kooch et al. (2012).	26
Table 14. Summary of study by Kooch et al. (2012).	27
Table 15. Comparison of study specifics.	32
Table 16. Regression equations predicting windthrow pit diameter (D) in meters as a function of tree DBH in centimeters for limited data set.	32
Table 17. Regression equations for all 676 observations.....	35

Preface

This study was conducted for the Levee Safety Program, Headquarters, US Army Corps of Engineers (HQUSACE). Tammy Conforti was the Program Manager.

The work was performed by the Geotechnical Engineering and Geosciences Branch (GS-G) of the Geosciences and Structures Division (GS), US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL), in collaboration with the USACE Institute for Water Resources Risk Management Center (RMC). At the time of publication, Chad A. Gartrell was Chief, CEERD-GS-G; Bartley P. Durst was Chief, CEERD-GS; and Dr. Mike Sharp, CEERD-GV-T, was the Technical Director for Water Resources Infrastructure. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

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Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
hectares (ha)	1.0 E+04	square meters
inches	0.0254	meters

1 Introduction

1.1 Background

To evaluate the potential influence of a tree on embankment stability, it is necessary to estimate the void that will occur in the embankment if the root system were to fail from storm loads. Currently, there is no published scientific literature focusing solely on this issue from an engineering perspective. This report provides a survey of existing literature for the purpose of developing a data set to estimate the void dimensions from an overturned tree.

Trees are most commonly overturned by winds during storms (Phillips et al. 2008). This event is termed *windthrow*. Because of the frequency of windthrow events, the majority of published information regarding overturning trees is centered on windthrow. Therefore, windthrow will be referred to frequently throughout this report.

1.2 Objective

The objective of this study was to develop a conservative envelope curve that could be used to predict the void dimensions from an overturned tree as a function of tree size. This was accomplished through a synthesis of existing literature regarding tree windthrow. The void that results from a tree windthrow event is termed the *windthrow pit*. This report summarizes existing research findings that contain data sets regarding the size of windthrow pits. An analysis of the data compared the various data sets graphically and statistically.

2 Overview of Tree Uprooting

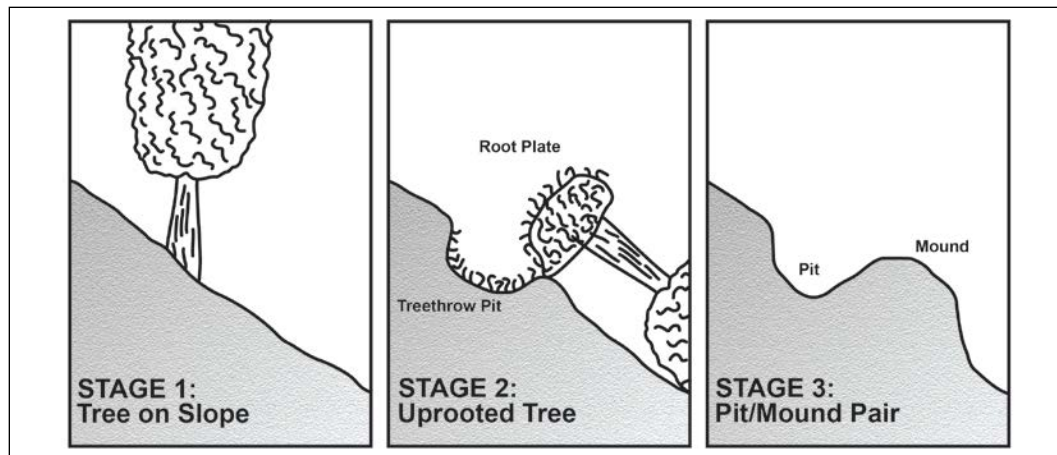
The term *tree uprooting* implies that a tree has overturned with most of its larger roots intact, thereby ripping a large portion of the roots and attached soil out of the ground (Schaetzl et al. 1989b). Tree uprooting has been studied extensively by numerous authors for purposes related to forestry, ecology, geomorphology, and sediment transport (Cooper-Ellis et al. 1999; Schaetzl et al. 1989a; Gallaway et al. 2009; Phillips et al. 2008). Because of the numerous reasons for which tree uprooting has been studied, terminology describing the process varies throughout the literature. The following sections provide an overview of terminology regarding tree uprooting, the mechanics of windthrow, and the factors that influence windthrow potential.

2.1 Terminology

Tree uprooting has also been called *root throw*, *tree fall*, *tree tip*, and *tree overturning* by various authors (Schaetzl et al. 1989b). These are generic terms that provide little information regarding how the tree was overturned. More descriptive terms also exist in which the forcing mechanism causing the tree to overturn is referenced. These include *windthrow*, *windfall*, *blowdown*, *windbreak*, *windblow*, *snow-throw*, and *snow-down* (Schaetzl et al. 1989b). As windthrow is the most common cause of tree overturning (Phillips et al. 2008), the remainder of the report refers to windthrow when discussing tree-uprooting phenomena.

A simple schematic illustrating a single tree windthrow event is given in Figure 1. The top leafy portion of the tree is called the tree *crown*. The forces due to wind are transferred from the crown to the soil through the tree trunk (also called the *bole*) and the roots. If the strength of the soil and the roots is exceeded by the load exerted on the tree by the wind, the tree will overturn, leading to a resulting *windthrow pit* and *root plate* pair. *Windthrow pits* have also been referred to as *depressions*, *craters*, and *tip-up pits* (Schaetzl et al. 1989b). The corresponding *root plate* has also been called a *root wad*, *root ball*, *root mound*, and *earth ball* (Schaetzl et al. 1989b). In this report, the terms *windthrow pit* and *root plate* will be used to describe the void and soil-root ball that occur from a windthrow event.

Figure 1. Schematic of tree overturning (Schaetzl 1989b, reprinted with permission).



When discussing dimensions of a root plate, it is common to refer to *root-plate length*, *root-plate width*, and *root-plate depth*. Typically, a root plate is elliptical, with the longest dimension usually being the side-to-side measurement (perpendicular to the trunk). Authors throughout the literature have not been consistent in the use of width and length. For the purposes of this report, length will always be taken as the longer axis of the ellipse while width will be taken as the shorter axis.

Coder (2010) provided a more formal definition of the root plate as follows:

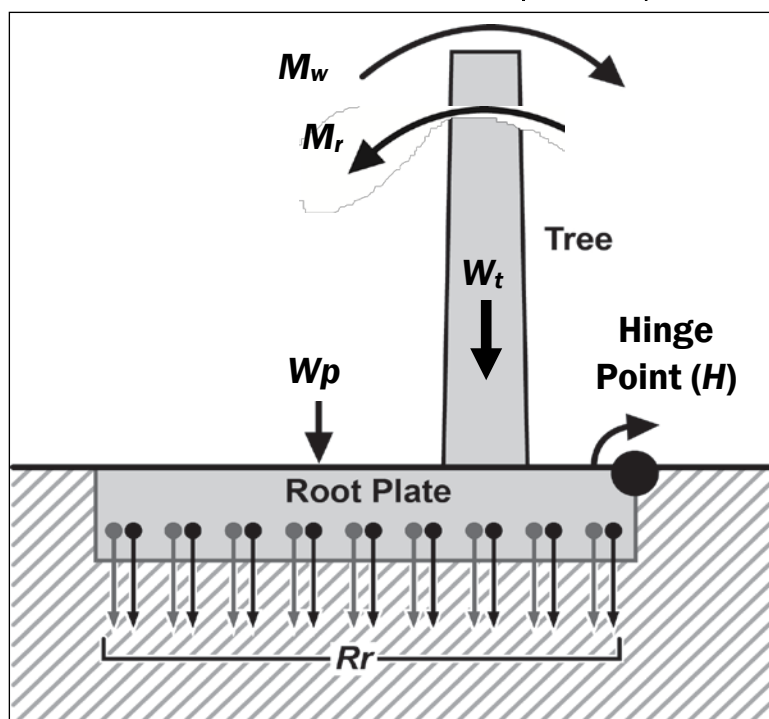
A tree root plate is composed of large diameter roots generated at the base of a stem. These large roots taper quickly away from the stem base. A point is reached along a large root where the structural dominance of root stiffness in supporting a tree shifts to dominance of root and soil tensile strength supporting a tree. This point of functional change in large roots represents the edge of a root plate. A tree root plate is a stiff, shallow, horizontal disk-shaped rooting area, and associated soil mass, under and near the stem base.

While this definition is not proven to be true by empirical evidence, it provides an illustrative definition by describing the function the root plate serves. A root plate acts as an almost rigid base from which the forces are transferred to the soil. This concept is further described through a discussion of the mechanics of windthrow in the following section.

2.2 Mechanics of windthrow

From a purely mechanical perspective, the event of tree windthrow is simply a matter of moment equilibrium. A diagram illustrating the forces acting on a tree during wind loading is given in Figure 2. The forces exerted by the roots and soil act on the boundary of the failure zone, as shown by the force distribution (R_r) in Figure 2. The weights of both the root plate (W_p) and the tree (W_t) add an additional resisting moment. The wind force creates the overturning moment (M_w), which is a function of tree frontal area, tree height, and wind speed. The resulting moments from all forces are calculated about the hinge point (H). This simplistic model, proposed by Achim and Nicoll (2009), neglects the bending and shearing of large horizontal roots on the leeward side. However, this neglected force can be easily accounted for by adjusting the distributed force (R_r).

Figure 2. Force diagram of tree windthrow event (adapted from Achim and Nicoll 2009, used with permission).



As a tree grows with age, the frontal area and the tree height increase in magnitude. When acted on by wind, this increase causes the resulting wind-induced moment also to increase in magnitude. In order for moment equilibrium to be satisfied and the tree to remain standing, the resisting moments must also increase in magnitude proportionally. Therefore, the root plate likely increases in size to offset the larger overturning moments.

This proportional change in size is referred to as an *allometric relationship*. Throughout the literature, allometric relationships have been used extensively with trees to estimate root distributions, biomass magnitudes, and tree heights (Tobin et al. 2007; Drexhage and Colin 2001; Clinton and Baker 2000; Jackson et al. 1996; Day et al. 2010). Therefore, it is reasonable to assume that such allometric relationships exist for root-plate dimensions and the resulting windthrow pit dimensions.

From a mechanics perspective, the root-plate width is much more significant than the root-plate depth because an increase in the root-plate width provides an increase in the moment arm that is used to calculate the resisting moment. An increase in root-plate depth increases the mass of the root ball and the zone of soil over which the soil strength is mobilized; however, it does not alter the moment arm about the overturning hinge (H). Because of this observation, it is expected that much stronger allometric relationships exist describing root-plate width than describing root-plate depth.

2.3 Factors influencing windthrow potential

Windthrow is a complex process that can be influenced by many parameters; however, despite the complexity, numerous studies have been published showing that statistical trends exist regarding the potential for windthrow. Peterson (2007) studied nine separate blowdown sites across North America and found that windthrow potential increases with increasing tree diameter. Peterson also found that conifer trees are much more likely to be blown down than deciduous trees. Phillips et al. (2008) independently came to the same conclusion that conifers have a higher potential for blowdown through a study of tornado blow-down sites in Arkansas. Phillips and associates also concluded that the size of a tree seems to be more important than soil characteristics with respect to both uprooting potential and the amount of soil disturbed in an uprooting event.

Slope has also been found to increase uprooting potential as well. Lenart et al. (2010) found that ground slope had a positive influence on uprooting rates. Numerous studies by other authors have also found that slope increases the potential for windthrow (Phillips et al. 2008; Gallaway et al. 2009; Cremeans and Kalisz 1988; Kellman and Tackaberry 1993).

Numerous other factors—such as tree species, soil type, and rooting depth—have been shown to influence uprooting potential (Peterson 2007). For a more in-depth review of factors influencing uprooting potential, the reader is referred to Peterson (2007).

3 Methods of Estimating Root and Pit Dimensions

Despite the numerous factors that influence windthrow potential, windthrow pit dimensions are consistently primarily related to tree size. This is due to the requirement that some degree of proportionality be maintained for the mechanical reasons previously discussed. This section provides an overview of various allometric relationships that have been used in the past to estimate windthrow pit and mound dimensions. Because the pit dimensions are significantly affected by the root extents, relationships for root extents and size are also presented, assuming that many of the same parameters will also affect windthrow pit dimensions. Regressions for root extents are not being presented for use in assessing pit dimensions. These regressions are simply being presented as it may be likely that regressions for root extents and regressions for pit dimensions share the same independent variable. Data sets are presented in the dimensions used by the authors of the particular study.

3.1 Crown width

Crown width (branch spread) has been used as a surrogate of root spread for decades. An example of regression between crown width and root spread is shown in Figure 3 as found by Smith (1964). Smith collected data on hundreds of windthrow events for coniferous trees in British Columbia and developed multiple regressions for each species. Smith found that while crown width had a strong correlation to root spread (R^2 of 0.87), the relationship varied significantly between species. This conclusion was also reached by Tubbs (1977); Day et al. (2010), and Gilman (1988). Additionally, after performing regressions of root spread from diameter at breast height (DBH), height, and crown width, Smith concluded that the addition of height and crown width to DBH in the regressions provided little additional value.

3.2 Tree height

To evaluate the use of tree height as a surrogate of root spread in urban environments, Day et al. (2010) compiled existing data from the literature. A summary plot of the findings from this study is shown in Figure 4. Note that each point in Figure 4 represents a study average. The studies were for

Figure 3. Crown - root relationship (adapted from Smith 1964).

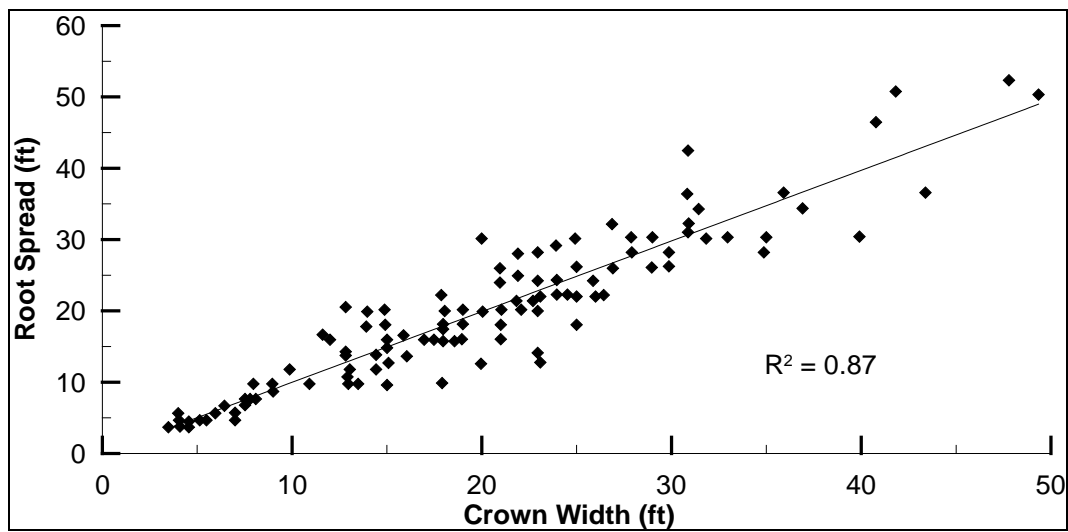
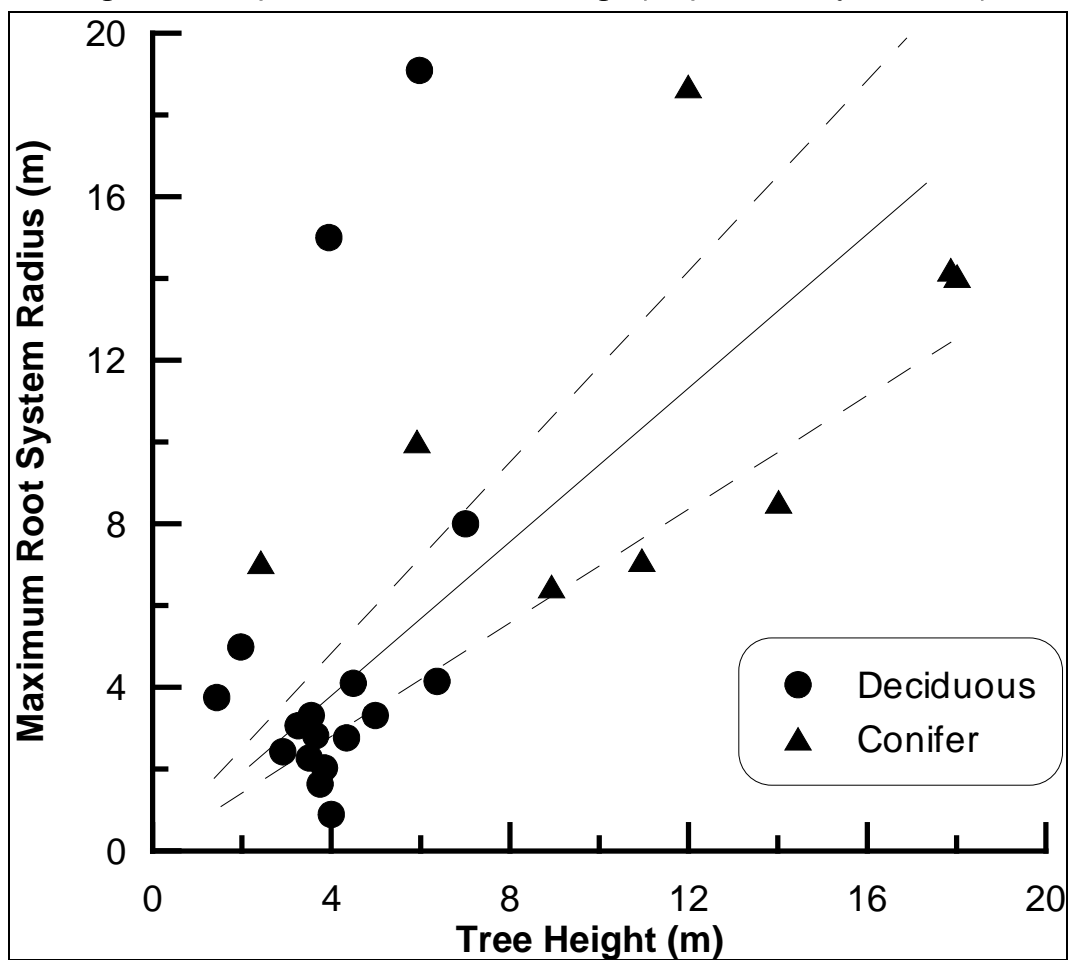


Figure 4. Root spread as a function of tree height (adapted from Day et al. 2010).



various species and locations. As seen in the figure, the majority of the data are plotted outside the 95% confidence intervals (dashed lines), supporting that tree height is a poor indicator of root spread. The variation in the data is easily explained due to the extrinsic variables that are not accounted for in this assessment (e.g., soil type, species, location, and slope). However, as the purpose of this study is to find a generalized relationship that is minimally influenced by these other factors, Day et al. (2010) illustrates clearly that tree height is a poor choice of independent variable for this study.

Statistically, Smith (1964) found that tree height was a poor indicator of root length even in a single location for the same species. This was confirmed by Smith's observation that trees of the same height can have very different root spreads between forest-grown trees and open-grown trees.

3.3 Tree diameter

Tree DBH has been used as the primary independent variable for numerous allometric relationships (Drexhage and Colin 2001; Gilman 1988; Peterson 2007; Lenart et al. 2010; Gallaway et al. 2009). This is in part because DBH is an easy measurement to make, but it also often yields the highest correlation to the dependent variable of interest. Drexhage and Colin (2001) found an extremely high correlation between DBH and root system biomass for 71 oak trees ($R^2=0.94$). Likewise, Putz (1983) found an extremely high correlation between DBH and windthrow pit volume, as shown in Figure 5. Numerous other authors found that the single strongest predictor of root dimensions (Smith 1964; Gilman 1988) and root-plate dimensions (Lenart et al. 2010; Achim and Nicoll 2009; Day et al. 2010) is tree DBH as well.

Not only does tree diameter yield the highest correlation to root and pit dimensions, but it also is the single independent variable that results in minimal influence of soil type, tree species, and climate on predictive relationships. This concept is illustrated clearly in a study performed by Lenart et al. (2010). Lenart and associates measured mound/pit area for 94 uprooted trees in Puerto Rico and performed a regression on the data. They then included an additional data set from Panama that had been collected by Putz (1983). Figure 6 shows a plot of both data sets. The resulting regressions from the data sets are given in Table 1. As can be seen from the regression equations, the data sets yield similar regressions even though they are for different species and locations. This illustrates that it may be possible for DBH to account for the majority of variation in root-

plate dimensions. This, combined with the fact that DBH is one of the most commonly reported independent variables, led the authors of this research to focus on DBH as the independent variable of choice for the purpose of this study.

Figure 5. Relationship between tree diameter and windthrow pit volume (adapted from Putz 1983).

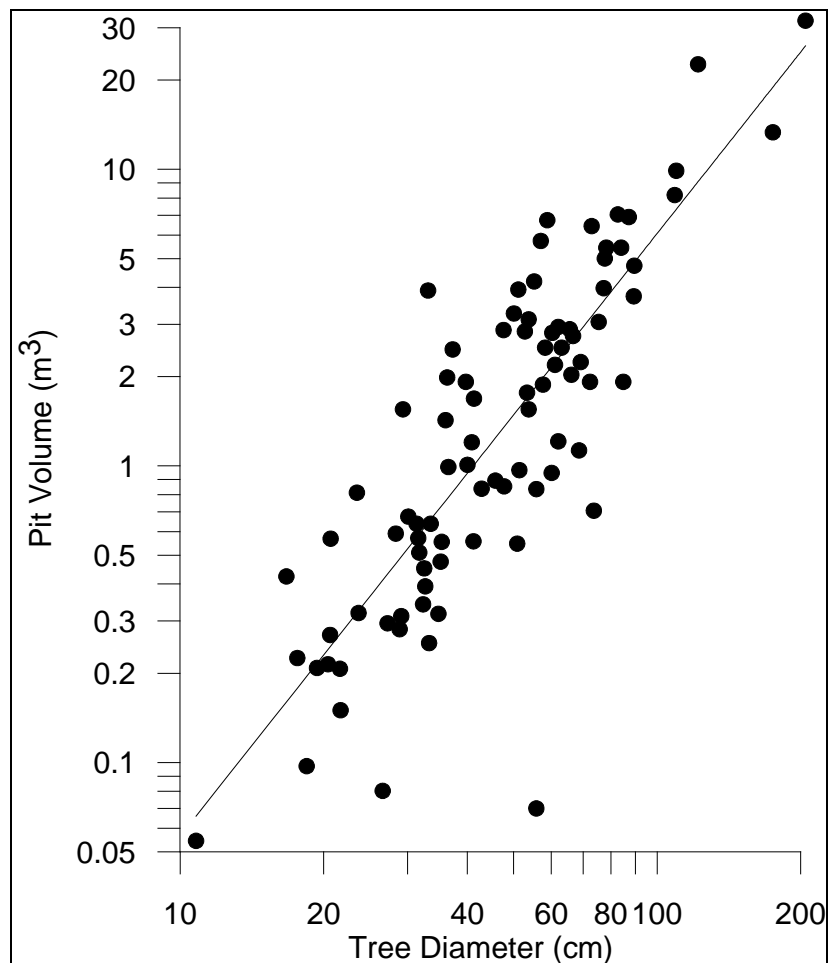


Figure 6. Linear regression of data adapted from Putz (1983) [triangles] and Lenart et al. (2010) [circles].

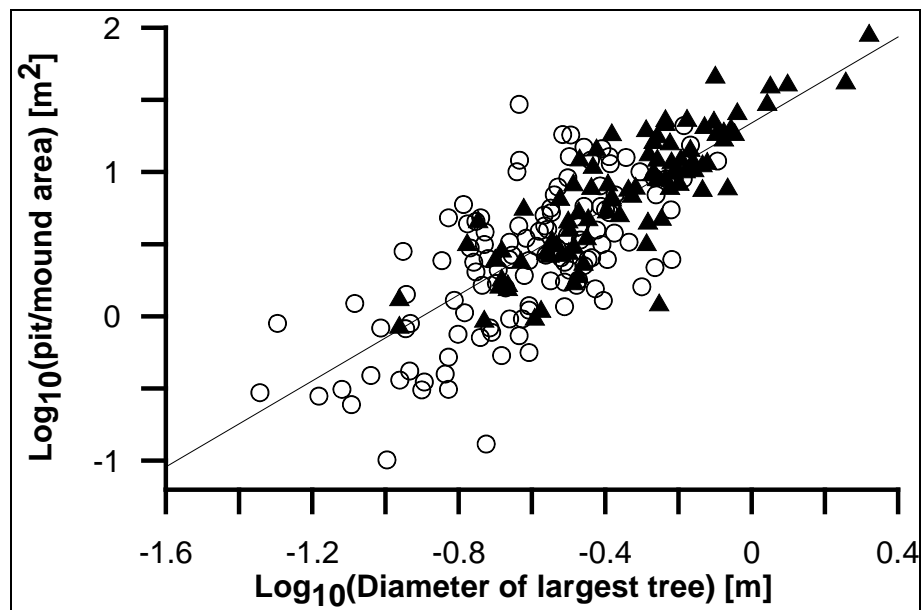


Table 1. Comparison of Puerto Rico and Panama data (Lenart et al. 2010).

Response (y)	Intercept	Slope	Predictor (x)	R ²	Data Frequency
Log ₁₀ (Mound/pit area, m ²), Panama data	1.35	1.51	Log ₁₀ (diameter, m)	0.68	94
Log ₁₀ (Mound/pit area, m ²), Panama and Puerto Rico data	1.34	1.49	Log ₁₀ (diameter, m)	0.61	211

4 Previous Studies

During a review of existing literature, the authors found that the majority of literature referencing tree pit/mound dimensions specifically studies issues related to forestry, ecology, soil dynamics, and geomorphology. Because of this, very little literature exists for the sole purpose of measuring pit dimensions as a function of tree characteristics; however, many studies contain information on pit characteristics and tree characteristics. The following sections summarize various studies from which the authors were able to extract valuable data regarding windthrow pit dimensions. For each paper referenced below, a summary of the work conducted by the various authors is provided. Additionally, descriptions and plots of the data that were digitized from the original research are given.

4.1 Distribution and characteristics of windthrow microtopography on the Cumberland Plateau of Kentucky (Cremeans and Kalisz 1988)

Cremeans and Kalisz (1988) performed extensive sampling of uprooting microtopography throughout the University of Kentucky's Robinson Forest as part of a study regarding the spatial distribution of uprooting microtopography. The purpose of the study was to determine if uprooting operates uniformly or nonuniformly over a mountainous landscape. Within this study, Cremeans and Kalisz encountered 524 uprooting microtopography sites. However, of the 524 sites, only 43 sites were estimated to have occurred within 5 to 10 years of the field survey. This number of valuable data points for the purposes of the current study was reduced even further, as 20 of the 43 uprooting events were judged to have been dead at the time of uprooting. The data presented in the original paper for these remaining 23 uprooting instances are shown in Figure 7. Only the surface area of the disturbed ground (mound or pit area) was reported. A summary of the study specifics is presented in Table 2.

4.2 Microsite variation and soil dynamics within newly created treefall pits and mounds (Peterson et al. 1990)

Peterson et al. (1990) performed a study focusing on microtopographic variation and the differences in plant colonization patterns for various microtopography sites created by new tree pits and mounds that resulted

Figure 7. Tree DBH versus area of ground disturbed (adapted from Cremeans and Kalisz [1988]).

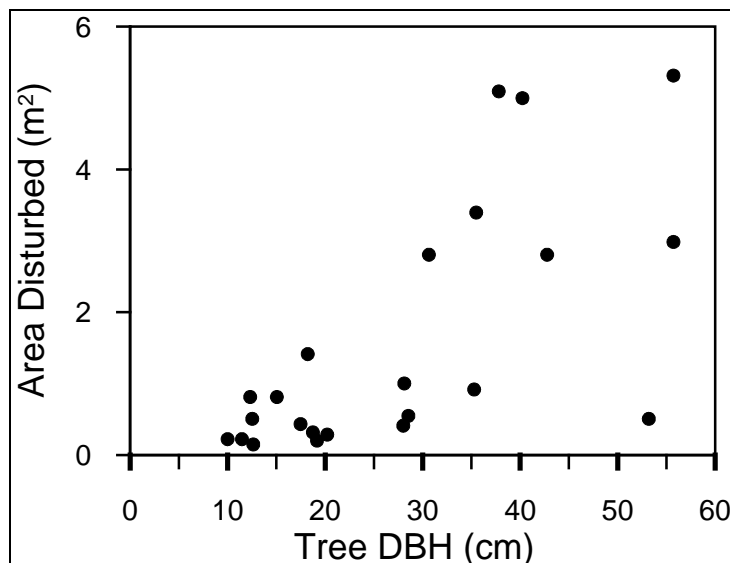


Table 2. Summary of study by Cremeans and Kalisz (1988).

Location:	Kentucky, USA
Date of Blowdown:	Unknown
Date of Measurements:	5 to 10 years after blowdown (estimated)
Tree Species:	<i>Quercus coccinea</i> (Scarlet Oak) <i>Quercus prinus</i> (Chestnut Oak) <i>Liriodendron tulipifera</i> (Yellow Poplar)
Climate:	Temperate Humid Continental
Sample Number:	23
Information Measured:	DBH, Pit Length, Pit Width, Mound Length, Mound Width

from a high wind event. As part of this study, Peterson and associates measured the pit dimensions for 28 trees that had blown down due to a tornado. The tornado occurred 31 May 1985 and destroyed 386 ha of old growth hemlock-northern hardwoods within the Allegheny National Forest in northwestern Pennsylvania. In November 1986, Peterson's group selected 12 American Beech trees and 16 Eastern Hemlock trees from the tornado blowdown area for which they measured DBH, mound height, mound width, pit depth, pit length, and pit width.

Of the 28 selected sites only the pit width and pit length data for 27 sites were available. A plot of the pit width and pit length as a function of DBH is shown in Figure 8. A summary of the study specifics previously mentioned is provided in Table 3.

Figure 8. Windthrow pit size data (adapted from Peterson et al. [1990]); (A) pit width and (B) pit length as a function of tree diameter at breast height (DBH).

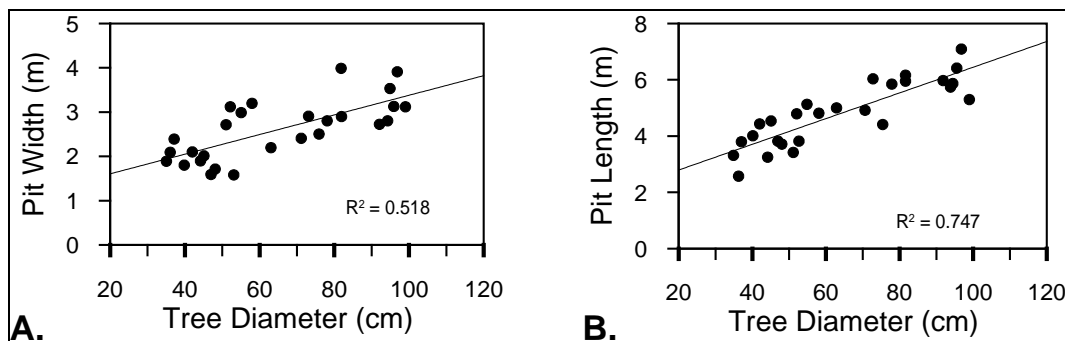


Table 3. Summary of study by Peterson et al. (1990).

Location:	Pennsylvania, USA
Date of Blowdown:	31 May 1985
Date of Measurements:	November 1986
Tree Species:	<i>Fagus grandifolia</i> (American Beech) <i>Tsuga Canadensis</i> (Eastern Hemlock)
Climate:	Humid Continental
Sample Number:	28 (only 27 digitized from original plots)
Information Measured:	pit length and pit width

4.3 Catastrophic windthrow in the southern Appalachians: characteristics of pits and mounds and initial vegetation responses (Clinton and Baker 2000)

In October of 1995, Hurricane Opal passed over the southern Appalachians, creating large areas of windthrow damage in the hardwood forests of the region. The center of the hurricane passed within 180 km of the Coweeta Basin in western North Carolina, causing numerous trees to be uprooted. Clinton and Baker surveyed 48 of the windthrow sites for the purposes of studying windthrow gap extent, characteristics of the windthrow sites in the region, pit-mound microclimate, and initial sprout responses on pit-mound microtopography. As part of this study, Clinton and Baker collected pit-mound dimensions on 48 pit-mound pairs. The data were reported in terms of biomass, using species-specific regressions; therefore, the data were not able to be extracted directly from the original paper. However, Dr. Barry Clinton was contacted and graciously provided the original data set on behalf of Coweeta Hydrologic Laboratory. The data collected pertaining to pit-mound dimensions are presented in Figure 9. Additionally, a summary of the study specifics is presented in Table 4.

Figure 9. Windthrow pit and mound dimensions (adapted from Clinton and Baker [2000]).

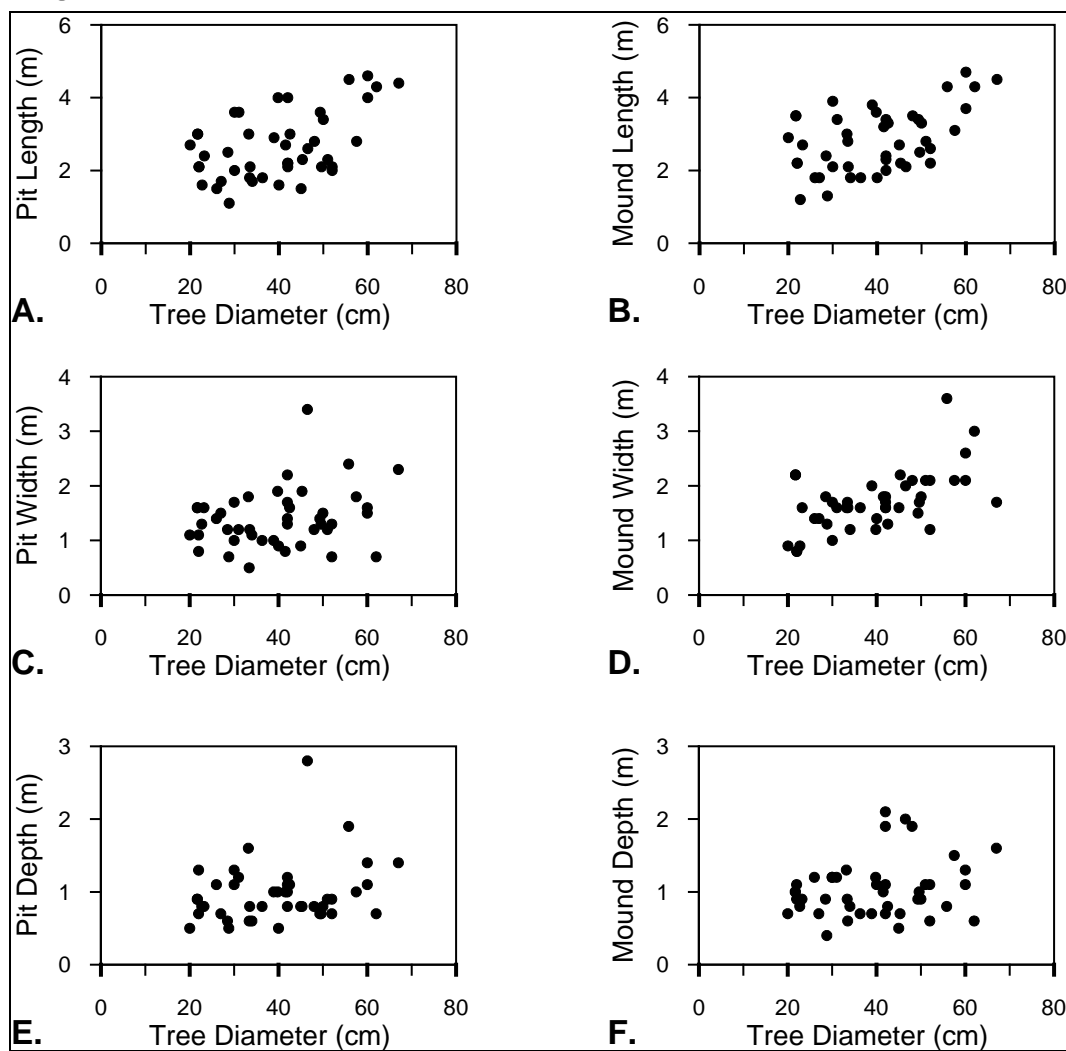


Table 4. Summary of study by Clinton and Baker (2000).

Location:	North Carolina, USA
Date of Blowdown:	October 4-5, 1995
Date of Measurements:	Summer of 1996
Tree Species: (most prominent species listed)	<i>Acer rubrum</i> (Red Maple) <i>Quercus coccinea</i> (Scarlet Oak) <i>Quercus prinus</i> (Chestnut Oak) <i>Liriodendron tulipifera</i> (Yellow Polar)
Climate:	Maritime, Humid Temperate
Sample Number:	48
Information Measured:	DBH, pit length, pit width, pit depth, mound length, mound width, mound depth

4.4 Damage and recovery of tree species after two different tornadoes in the same old-growth forest: A comparison of infrequent wind disturbances (Peterson 2000)

In August of 1994, a tornado event passed through the Tionesta Research Natural Areas in the Allegheny National Forest of northwestern Pennsylvania. The path of the tornado was located approximately 3 km south of the area that Peterson et al. (1990) had previously studied, allowing for Peterson (2000) to focus on studying regeneration and recovery for two distinct storm events in the same forest. As part of this study, Peterson measured the pit length and pit width of 84 windthrown trees. Additional measurements included tree DBH, tree location, and tree orientation. One of the unique observations found by Peterson was that the relationship between tree size and the pit area was consistent despite obvious differences in the moisture conditions of the soil for each event (1985 tornado and 1994 tornado).

From Peterson, the pit area for the 84 tree sites sampled was reported. A plot of the pit area as a function of tree DBH is shown in Figure 10. A summary of the study specifics is provided in Table 5.

Figure 10. Windthrow pit dimensions for Tionesta Scenic and Research Natural Area (adapted from Peterson [2000]).

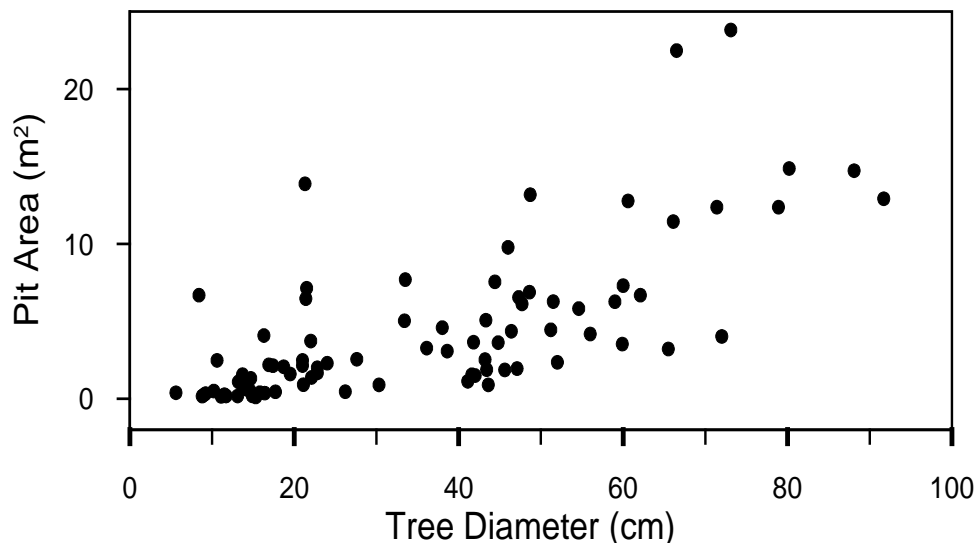


Table 5. Summary of study by Peterson (2000).

Location:	Pennsylvania, USA
Date of Blowdown:	28 August 1994
Date of Measurements:	July 1996
Tree Species:	<i>Fagus grandifolia</i> (American Beech) <i>Tsuga Canadensis</i> (Eastern Hemlock)
Climate:	Humid Continental
Sample Number:	84
Information Measured:	DBH, pit length, pit width

4.5 Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns (Peterson 2007)

Peterson (2007) assessed the influence of tree diameter and species on tree damage statistics for nine tornado blowdown events that occurred in North America. A few of the data sets used for comparison purposes in this paper were previously discussed in the preceding two sections. While no data set is directly reported in Peterson, the authors of this study obtained directly from Dr. Chris Peterson one of the data sets used for comparison purposes. This data set was titled ‘Taylor’ in Peterson and refers to a tornado blowdown event that occurred in northeastern Pennsylvania during May of 1998. The blowdown damage was sampled by Peterson during 2000-2001. The measurements taken were tree DBH, tree location, pit length, pit width, mound length, and mound width. Figure 11 shows the resulting pit length, pit width, and pit area data as a function of DBH. Table 6 provides a summary of the study specifics.

4.6 Salvage logging after windthrow alters microsite diversity, abundance, and environment, but not vegetation (Peterson and Leach 2008)

Leach (2003) published a thesis at the University of Georgia in which the immediate forest response to a downburst event (straight line thunderstorm) was documented. Additionally, Leach evaluated the influence of salvage logging operations on the forest recovery and resulting species diversity by comparing portions of the downburst area that had been salvage logged to portions that had not (Peterson and Leach 2008). As part of these studies, measurements were taken on numerous trees that had blown down due to a downburst that occurred 5 May 1999 in the Natchez Trace State Forest (NTSF) of west-central Tennessee (Leach 2003). Pit length, pit width, mound length, mound width, and tree DBH were recorded for 94 trees that had been overturned during the summer of 2001.

Figure 11. Data for tornado blowdown site titled 'Taylor' in Peterson (2007): (A) pit length, (B) pit width, and (C) pit area.

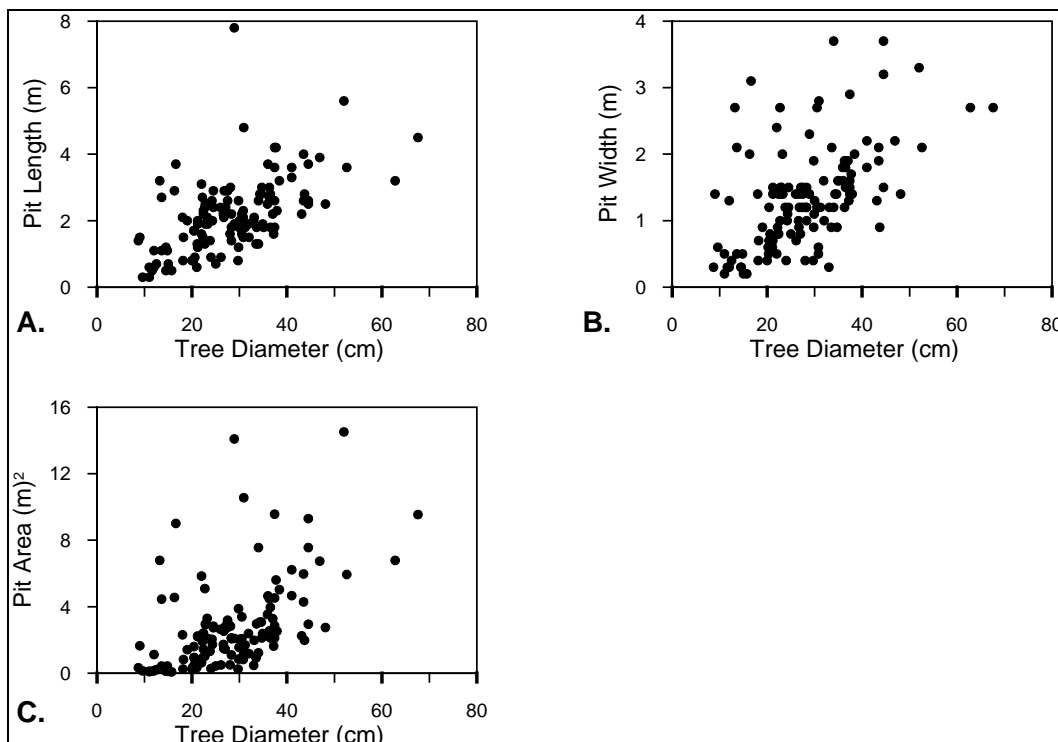


Table 6. Summary of study specifics for 'Taylor' site in Peterson (2007).

Location:	Pennsylvania, USA
Date of Blowdown:	May 1998
Date of Measurements:	2000-2001
Tree Species (Primary):	<i>Acer rubrum</i> (Red Maple) <i>Acer saccharum</i> (Sugar Maple) <i>Quercus alba</i> (White Oak) <i>Fagus grandifolia</i> (American Beech) <i>Betula alleghaniensis</i> (Yellow Birch)
Climate:	Humid Continental
Sample Number:	128
Information Measured:	DBH, pit length, pit width, mound width, mound length

The original data reported in Leach (2003) and Peterson and Leach (2008) were obtained by the authors from Dr. Chris Peterson. Pit area and mound area as a function of tree DBH are shown in Figure 12. One issue that was noted by Leach (2003) was the fact that the mound area exhibited less scatter than the pit area in this data set. One possible explanation may be that the measurements were taken nearly two years after the blowdown event and salvage logging had occurred in a few of the areas. The pits may

have been more vulnerable to disturbance and infilling than the mounds, creating more scatter in the measured data. Immediately after tree overturning, the windthrow pit/mound should be nearly identical in size. Because of the additional scatter observed in the pit area data for this data set, the authors chose to represent the data by the recorded mound area values. A summary of the study details is provided in Table 7.

Figure 12. (A) Pit area and (B) corresponding mound area from Peterson and Leach (2008) and Leach (2003).

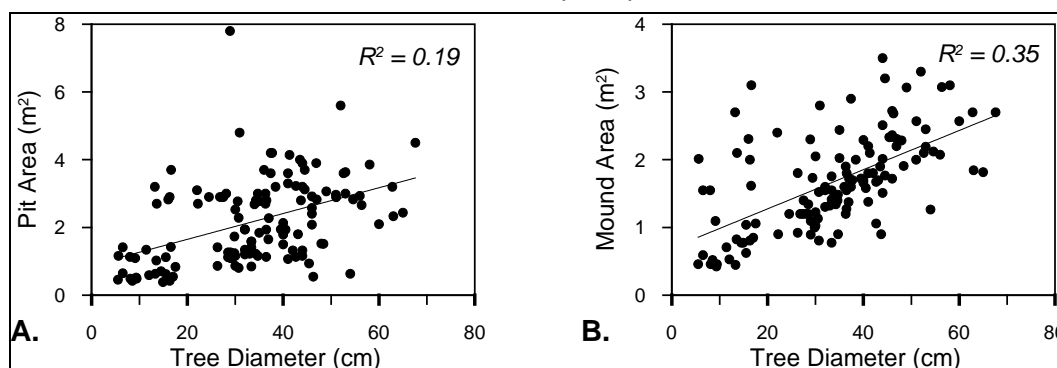


Table 7. Summary of study by Leach (2003) and Peterson and Leach (2008).

Location:	Tennessee, USA
Date of Blowdown:	5 May 1999
Date of Measurements:	June – August 2001
Tree Species:	<i>Pinus taeda</i> L. (Loblolly Pine) <i>Quercus</i> spp. (Oaks) <i>Carya</i> species (Hickories)
Climate:	Humid Continental
Sample Number:	94
Information Measured:	DBH, pit width, pit length, mound width, mound length

4.7 Pedologic and geomorphic impacts of a tornado blowdown event in a mixed pine-hardwood forest (Phillips et al. 2008)

In November of 2005, a severe storm produced 24 confirmed tornadoes that touched down throughout central and north-central Arkansas. Many of these tornadoes touched down within the Ouachita National Forest, located in western Arkansas and eastern Oklahoma. Phillips et al. (2008) surveyed two locations in which tornadoes touched down at North Alum Creek and Rock Creek in the northeast corner of Ouachita National Forest shortly after the storms (the time between the tornado and field measurements is unknown). The purpose of this study was to examine the

soil and geomorphic disturbances caused by the severe blowdown events. More specifically, this study looked at the relationships between tree growth, pedogenesis (soil formation), and bedrock weathering. Therefore, the volume of soil and rock that was being moved by the overturned trees was of primary interest. To obtain this information, Phillips and associates took measurements of the root wad (versus the corresponding pit) that resulted from the wind events. The specific measurements taken were tree DBH, mean root wad depth, root wad width, root wad length, and root wad volume.

From Phillips and associates, only root wad depth, surface area, and volume were available (see Figure 13) due to the data that the original authors reported in their figures. Another issue that arose with this data set is the unknown time between the storm event and the field measurements. If a long delay occurred, the root wad measurements could be smaller than the original pit dimensions that would have occurred. A summary of the study specifics is provided in Table 8.

Figure 13. Windthrow root wad dimensions (adapted from Phillips et al. 2008): (A) mean root wad depth, (B) surface area of uprooted soil mass, and (C) volume of uprooted soil mass as a function of tree DBH.

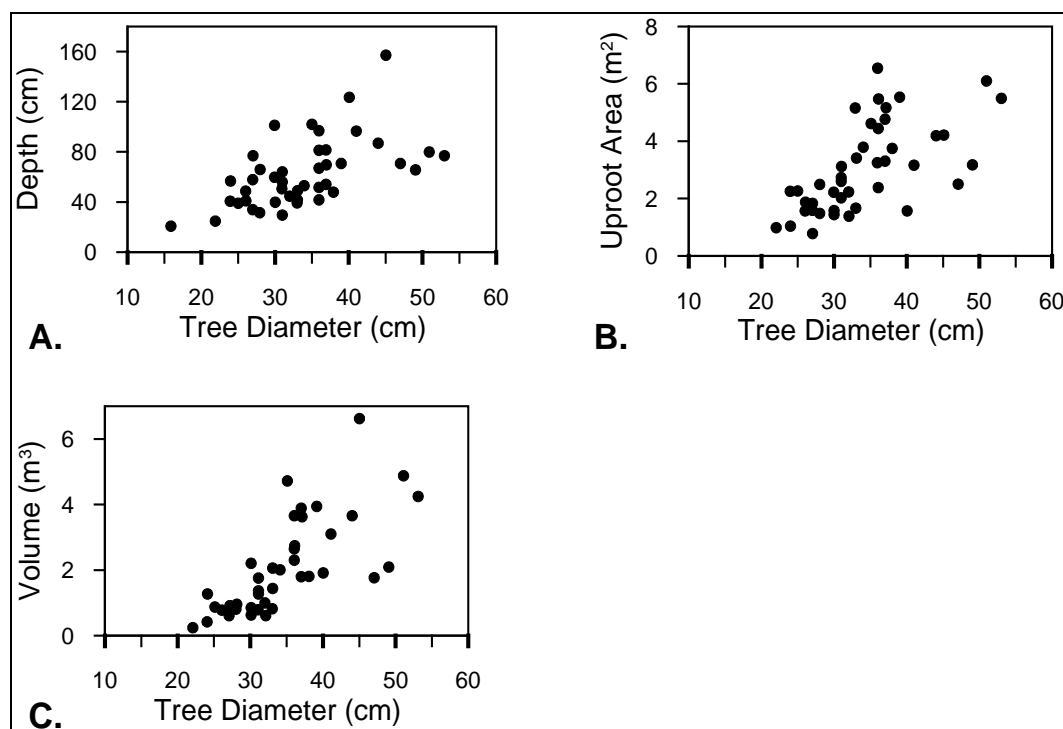


Table 8. Summary of study by Phillips et al. (2008).

Location:	Arkansas, USA
Date of Blowdown:	27 November 2005
Date of Measurements:	Unknown
Tree Species:	<i>Pinus echinata</i> (Shortleaf Pine) <i>Quercus</i> spp. (Oaks)
Climate:	Humid Subtropical
Sample Number:	45
Information Measured:	DBH, mound length, width, and mean depth

4.8 Modeling the anchorage of shallow-rooted trees (Achim and Nicoll 2009)

Achim and Nicoll (2009) developed a numerical model that could be used to predict the anchorage strength of Sitka spruce by using simple mechanistic rules. The model that was developed assumes a tree overturns about a hinge that occurs where the root plate intercepts the ground. To obtain data for the development of the model, Achim and Nicoll compiled data from tree pulling experiments that were conducted between 1993 and 2002.

Altogether, 148 trees were overturned at eight forest sites in the United Kingdom (Wauchope, Castlemilk, Glentool, Rumster, Leanachan [two locations], Kershope, and Eskdalemuir). For each tree that was overturned, the measurements that were recorded included maximum applied load before tree failure, maximum stem deflection, stem dimensions, crown dimensions, tree height, and root-plate dimensions. Statistical regressions were then conducted using all of the collected data. The results concluded that tree DBH was the best single predictor of root-plate dimensions. The data set obtained for lateral root-plate diameter is shown in Figure 14.

While DBH was the best single variable predictor of root-plate dimensions, including soil type as a variable accounted for another 12% of the variation in the data set; however, Achim and Nicoll found that the influence of tree DBH on lateral diameter was the same across all soil types (the slope of the regression line is parallel for all soil types).

From Achim and Nicoll (2009), only the lateral diameter versus DBH dataset was digitized because, as determined by their study, the root plate could be characterized by a semi-circle with the lateral diameter representing the diameter. A summary of study specifics is provided in Table 9.

Figure 14. Tree DBH versus lateral root-plate diameter data (adapted from Achim and Nicoll 2009).

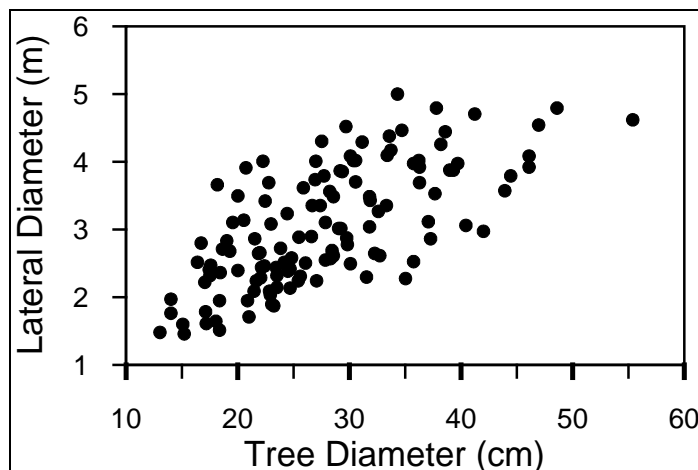


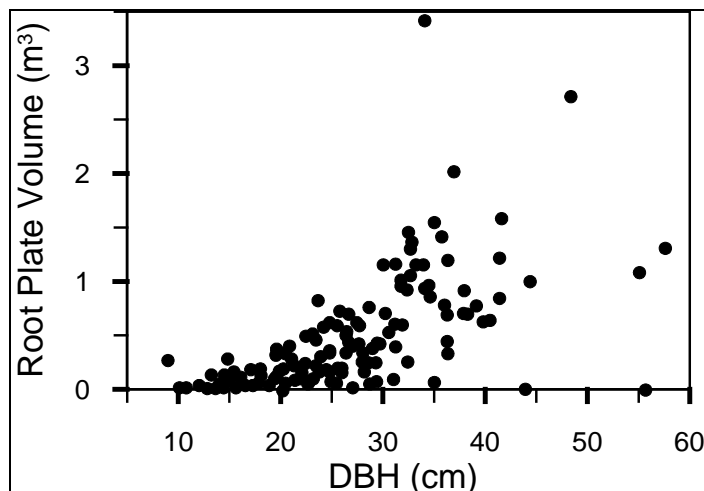
Table 9. Summary of study by Achim and Nicoll (2009).

Location:	United Kingdom
Date of Blowdown:	1993 - 2002
Date of Measurements:	Immediately following tree pull-down, (1993-2002)
Tree Species:	<i>Picea sitchensis</i> (Sitka Spruce)
Climate:	Temperate
Sample Number:	148
Information Measured:	DBH, root-plate dimensions, crown dimensions, turning moments required for overturning, peak deflections

4.9 Sediment transport due to tree root throw: integrating tree population dynamics, wildfire, and geomorphic response (Gallaway et al. 2009)

Tree overturning events result in vertical and horizontal displacement of sediment attached to the roots (root plate). From a geomorphic perspective, the volume of soil moved during tree overturning and the factors that influence the rate of tree overturning are of particular interest for estimating sediment transport rates in forest environments. Gallaway and associates (2009) investigated the influence of wildfire on the transport rates by monitoring tree overturning in a wildfire area. As part of this study, Gallaway and associates measured the root-plate dimensions of numerous trees over the course of a few years following a wildfire event. Because sediment transport rates were of interest, only root-plate volume was reported in the paper, as shown in Figure 15 .

Figure 15. Root-plate volume data (adapted from Gallaway et al. 2009).



From Gallaway and associates, only root-plate volume data could be obtained. Also, because both old and new overturned trees were catalogued, weathering and fire could have caused some of the measurements to have artificially low volumes. This explains many of the extremely low volume root plates seen in the data shown in Figure 15. A summary of the study details is provided in Table 10.

Table 10. Summary of study by Gallaway et al. (2009).

Location:	Hawk Creek, Kootenay National Park, British Columbia
Date of Blowdown:	Unknown
Date of Measurements:	2004 and 2005 (following July 2003 wildfire)
Tree Species:	<i>Pinus contorta</i> (Lodgepole Pine) <i>Picea engelmannii</i> (Engelmann Spruce) <i>Abies lasiocarpa</i> (Subalpine Fir)
Climate:	Temperate
Sample Number:	166
Information Measured:	DBH, root plate dimensions, slope, fall dimensions

4.10 Estimating soil turnover rate from tree uprooting during hurricanes in Puerto Rico (Lenart et al. 2010)

Lenart et al. (2010) collected root plate dimensions on trees that were overturned due to a hurricane in Puerto Rico as part of a study estimating soil turnover rate. Soil turnover rate was of particular interest to achieve an understanding of long-term terrestrial carbon dynamics because soil turnover increases atmospheric carbon through decomposition. To

accomplish these objectives, Lenart and associates took detailed measurements on 72 uprooted trees from 23 September through 20 December 1998 throughout Puerto Rico. The trees had blown down as a result of Hurricane Georges, which passed over Puerto Rico on 21 and 22 September 1998.

The sampled trees consisted of needleleaf, palm, and broadleaf trees. For each tree, the measurements taken consisted of DBH, pit length, pit depth, ground slope, and treefall direction. The shape of the mound/pit was recorded for the purpose of calculating soil turnover area and volume. Rather than DBH, trunk area was reported as the independent variable, as this allowed for the summation of the areas from multiple trees when clusters of trees overturned as a group.

From the study by Lenart et al. (2010), mound area and mound volume data were extracted. The data as presented in their study are plotted in Figure 16. A summary of the study specifics is provided in Table 11.

Figure 16. (A) Mound area and (B) mound volume as a function of trunk area (adapted from Lenart et al. 2010).

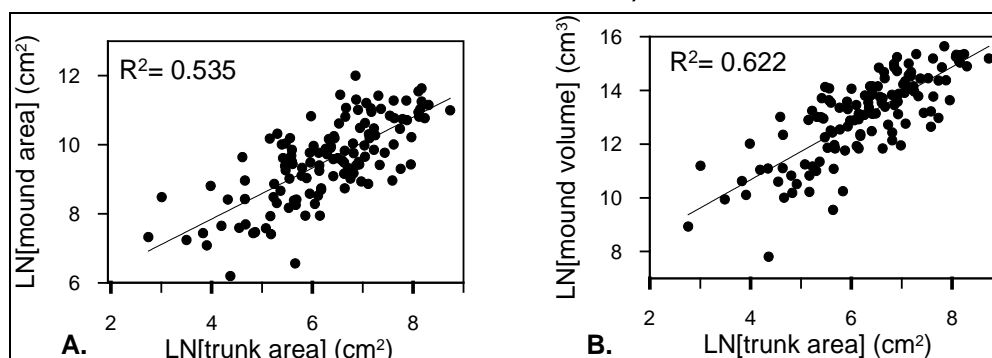


Table 11. Summary of study by Lenart et al. (2010).

Location:	Puerto Rico
Date of Blowdown:	21 – 22 September 1998
Date of Measurements:	23 September – 20 December 1998
Tree Species:	<i>Pinus caribaea</i> (Needleleaf) <i>Prestoea montana</i> (Palm) Numerous broadleaf species
Climate:	Tropical
Sample Number:	72
Information Measured:	DBH, pit length, pit depth, ground slope, treefall direction

4.11 The influence of windthrow microsites on tree regeneration in a mountain old growth forest (Simon 2010)

Simon (2010) [see also Simon et al. 2011] investigated the tree regeneration response to windthrow-generated microsites in European mountain forests. The specific goal of the study was to investigate the seed trapping ability of the various microsites as well as the corresponding seedling survival rate. As part of this study, measurements were taken on 70 windthrow generated pit-mound pairs that had resulted from windthrow events occurring in 1966, 1990, and 2007. The measurements were taken in July and August of 2008 and included tree DBH, pit depth, pit length, pit width, and direction of dip. While the raw data collected were not presented in Simon (2010) or Simon et al. (2011), Simon graciously provided the raw measurement data to the authors of this study. The data are presented in Figure 17. A summary of the study is provided in Table 12.

One issue that arose with this particular data set was the variation in age of pit-mound pairs at the time of measurements. Many of the sites surveyed were approximately 40 years of age. It is expected that due to weathering and other forms of natural disturbance (animal activity, organic material distribution, and vegetation growth), a windthrow pit of this age has significantly altered dimensions as compared to the original pit. Because of this, the authors expect that this data set may exhibit larger variance than many of the other data sets collected immediately following a windthrow event.

Figure 17. Windthrow pit dimensions from Simon (2010).

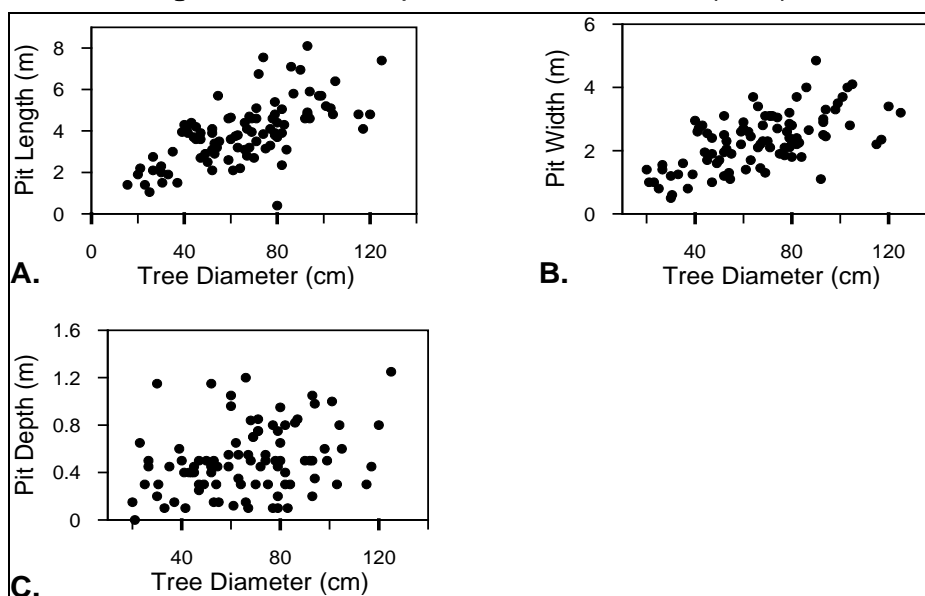


Table 12. Summary of study by Simon (2010).

Location:	Rothwald Old Growth Forest, Austria
Date of Blowdown:	1966, 1990, and 2007
Date of Measurements:	July – August 2008
Tree Species:	<i>Picea abies</i> (Norway Spruce) <i>Abies alba</i> (European Silver Fir) <i>Fagus sylvatica</i> (European Beech)
Climate:	Submaritime to Subcontinental
Sample Number:	70
Information Measured:	DBH, pit length, pit width, pit depth, dip direction

4.12 Effects of uprooting tree [sic] on herbaceous species diversity, woody species regeneration status, and soil physical characteristics in a temperate mixed forest of Iran (Kooch et al. 2012)

Kooch et al. (2012) studied the effect of tree overturning on the development of herbaceous plant species, woody species regeneration, and soil characteristics. As part of this study, measurements were taken on 34 uprooted trees located in a temperate forest of Mazandaran Province in northern Iran during the summer of 2009. The trees had overturned as a result of several windthrow events that occurred from 2005 to 2006. The parameters measured included tree DBH, tree length, pit length, pit width, pit depth, mound height, mound width, and mound thickness.

From Kooch et al. (2012), only mean measurements for each species group were reported. The data available are tabulated in Table 13. A summary of the study specifics is provided in Table 14.

Table 13. Pit and tree measurements from Kooch et al. (2012).

Species	No. Sampled	Mean DBH (cm)	Mean Pit Width (m)	Mean Pit Length (m)	Mean Pit Depth (m)
<i>Fagus orientalis</i>	18	59.5	3.20	1.38	0.71
<i>Carpinus betulus</i>	11	44	3.33	1.48	0.73
<i>Acer cappadocicum</i>	2	37	2.83	1.56	0.61
<i>Tilia platyphyllos</i>	2	38	2.88	1.51	0.61
<i>Parrotia persica</i>	1	37	2.86	1.39	0.61

Table 14. Summary of study by Kooch et al. (2012).

Location:	Mazandaran Province, Iran
Date of Blowdown:	2005 to 2006
Date of Measurements:	Summer of 2009
Tree Species:	<i>Fagus orientalis</i> (Beech) <i>Carpinus betulus</i> (Hornbeam) <i>Acer cappadocicum</i> (Maple) <i>Tilia platyphyllos</i> (Lime Tree) <i>Parrotia persica</i> (Ironwood)
Climate:	Temperate
Sample Number:	34
Information Measured:	DBH, tree length, pit length, pit width, pit depth, mound height, mound width, mound thickness

4.13 Other studies in the literature

Numerous other authors have conducted studies regarding various features of windthrow pits and mounds. However, the studies not explicitly mentioned above did not have individual data points available in the literature for use in this study. A few of the more notable studies are mentioned in the following paragraphs.

Beatty and Stone (1986) conducted a study in which 35 pit-mound pairs were surveyed from recent tree fall events. The purpose of this study was to develop a classification scheme for different tree fall types (ball –and– socket-type rotation versus a tipping plate rotation) as well as to document the physical and chemical properties of the tree fall microsites. While this study is widely cited throughout the literature, it was not used for this study. Only the average pit dimensions for each tree fall category were presented, and no indicator of tree size was provided. Therefore, no data (not even averages) were able to be taken for this study.

Norman et al. (1995) investigated the influence of slope on the net downslope soil mass movement caused by tree uprooting. As part of this study, 186 root-mound pairs were surveyed. The influence of slope on the pit dimensions was assessed to determine if slope increased or decreased the amount of material that was transported downhill due to tree uprooting. Unfortunately, because slope was the primary variable of interest, none of the data were presented in the paper as a function of tree size. Without the tree size data, this data set could not be included in the regressions developed in this study. Norman and his associates were contacted to see if the data set was available; unfortunately, the authors

were no longer involved in this research and had not retained a copy of the data. However, this study is discussed in more detail in the latter portions of this report regarding the influence levee slope may have on the pit dimensions resulting from a tree windthrow event.

5 Data Analysis

Due to the vast differences in objectives among the various studies previously mentioned, the forms of data that exist vary. While this prohibits direct comparisons, making a few assumptions allows the data sets to be compared. It is assumed for the purpose of data analysis that each root plate is circular. This allows root-plate diameter to be calculated for datasets that are reported in terms of measured area. It is also assumed that each data point in the literature represents a single tree. In a few cases, the sum of trunk area for a cluster of overturned trees was reported. The following sections describe the assumptions applied to each data set and present the resulting data. Additionally, statistical regression of the complete data set is used to develop a mean best-fit equation predicting equivalent circular root-plate diameter as a function of tree DBH. Suggested relationships regarding root-plate depth are compared to the limited data available in order to develop depth criteria as well.

5.1 Windthrow pit diameter

5.1.1 Area to equivalent circular diameter

Cremeans and Kalisz (1988); Lenart et al. (2010); Peterson and Leach (2008); Peterson (2000); and Phillips et al. (2008) reported the surface area of the root plate. The surface area of the root plate may be analogous to the surface area of the ground that was disturbed during uprooting. In order to obtain equivalent circular diameter (D_{eq}) from these data sets, it was simply assumed that all root plates were circular. Therefore, for the data extracted from Lenart et al. (2010) and Phillips et al. (2008), D_{eq} is calculated as

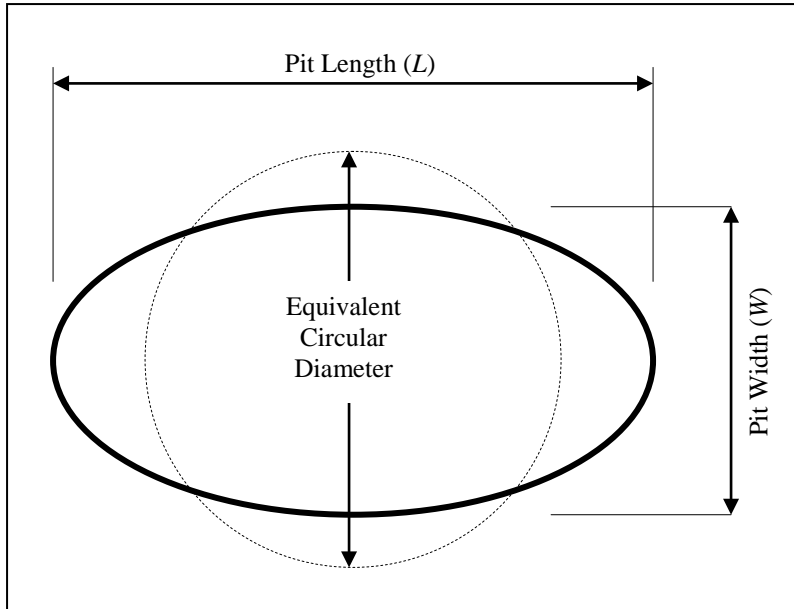
$$D_{eq} = 2 * \sqrt{\frac{\text{Elliptical Pit Area}}{\pi}} \quad (1)$$

5.1.2 Pit width and length to equivalent circular diameter

Peterson et al. (1990), Clinton and Baker (2000), Peterson (2007), Simon (2010), and Kooch et al. (2012) reported windthrow pit width and pit length dimensions. To convert pit width (W) and length (L) dimensions

into an equivalent circular diameter, it was assumed that the original pit shape was an elliptical shape, as shown in Figure 18.

Figure 18. Illustration of equivalent circular diameter.



The ground surface area disturbed by an elliptical pit with dimensions W and L as shown in Figure 12 is calculated as

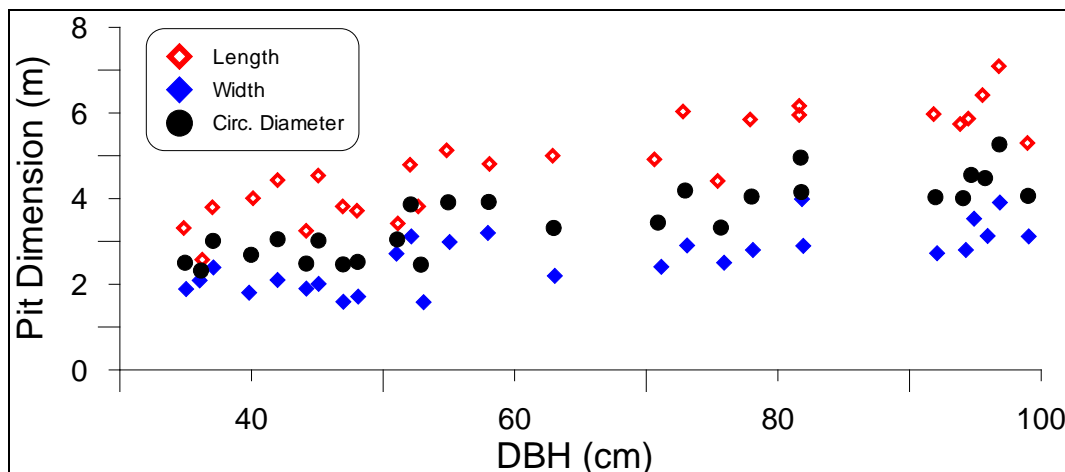
$$\text{Elliptical Pit Area} = \pi \frac{L}{2} \frac{W}{2} \quad (2)$$

Then, the equivalent circular diameter (D_{eq}) is calculated by solving for the diameter of a circle for which the area is equal to the elliptical pit area. D_{eq} is computed as

$$D_{eq} = 2 * \sqrt{\frac{\text{Elliptical Pit Area}}{\pi}} \quad (3)$$

The influence that computing D_{eq} in this manner has on the data is illustrated in Figure 19 by showing how this assumption transforms the data from Peterson et al. (1990). As can be seen by Figure 19, this method effectively averages the pit length and pit width measurements while keeping the surface area constant.

Figure 19. Original and equivalent circular data using pit dimensions and DBH from Peterson (1990).



5.1.3 Comparison and analysis of pit diameter data

The data from Peterson et al. (1990); Phillips et al. (2008); Lenart et al. (2010); and Kooch et al. (2012) are shown plotted in Figure 20. A best-fit linear regression performed on the data yields a correlation coefficient of 0.8576, indicating that there is a strong relationship between DBH and windthrow pit diameter. The resulting best-fit line and 95% confidence intervals are shown in Figure 20. This limited portion of all of the data was selected to be plotted because it yielded the highest correlation with the widest range of climate, soil type, and species. This is important, as it allows the following paragraph to be stated.

In addition to being a very strong fit, it should be noted that the data from these four studies are for very different tree species from different climates (see Table 15). Therefore, it can be argued that the mechanical relationship between tree size and root-plate size governs the resulting windthrow pit size. So, all things considered, increasing DBH results in increasing root-plate diameter. Based on these observations, it is reasonable to apply the linear relationships given for circular pit diameter to all trees in all locations. While these observations justify the rationale to use an empirical relationship across a wide geographic region, the data presented are a limited portion of the data collected. The remainder of this section will evaluate the entire data set as a whole, recognizing that it is reasonable to assess relationships solely based on DBH for the reasons just discussed.

Figure 20. Comparison of pit diameter data.

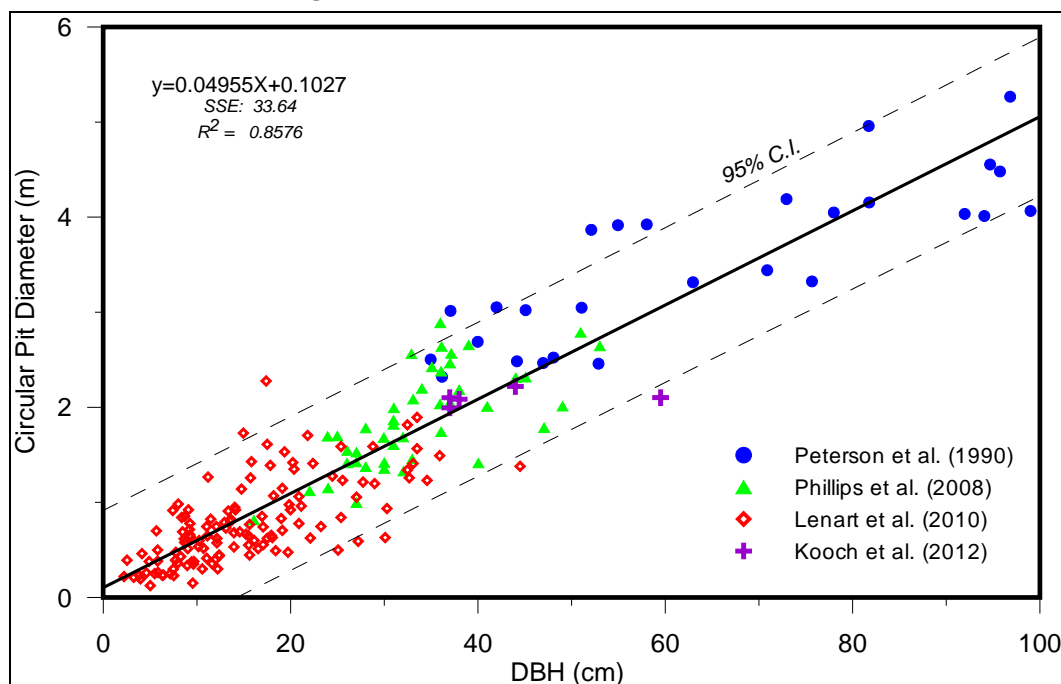


Table 15. Comparison of study specifics.

	Location	Tree Type	Soil Type	Climate
Peterson et al. (1990)	Pennsylvania	Beech, Hemlock	Silty sand (inferred)	Humid Continental
Phillips et al. (2008)	Arkansas	Shortleaf Pine, Oaks	Silty sand to clayey sand	Humid Subtropical
Lenart et al. (2010)	Puerto Rico	Needleleaf, Palm	Clay	Tropical
Kooch et al. (2012)	Iran	Beech, Hornbeam, Maple	Clay	Temperate

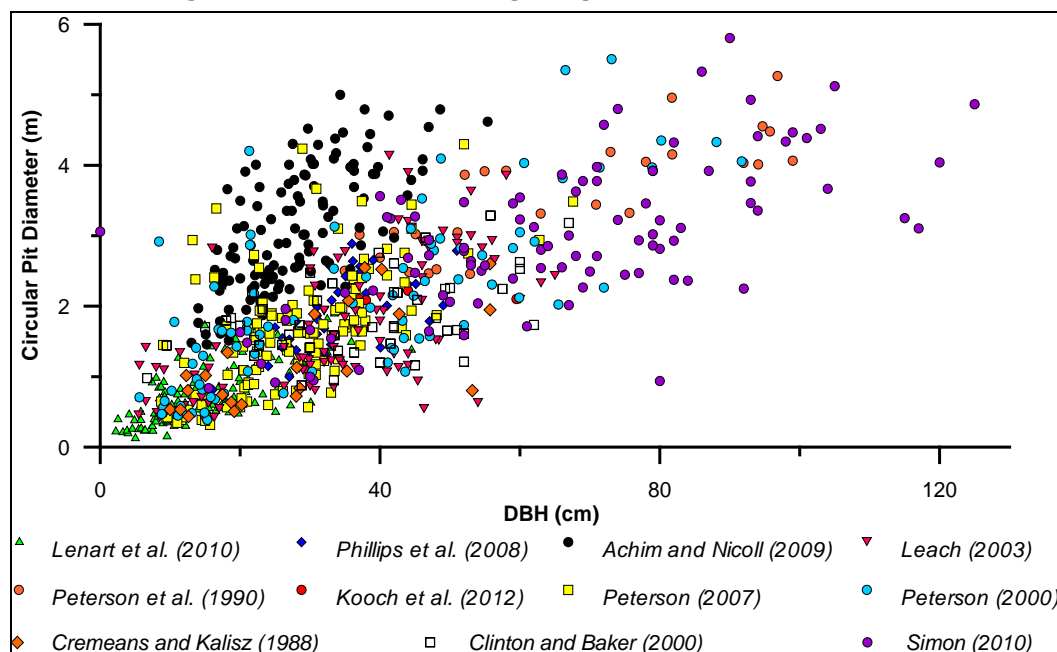
Table 16. Regression equations predicting windthrow pit diameter (D) in meters as a function of tree DBH in centimeters for limited data set.

Mean:	$D = 0.050 * DBH + 0.1027$
Upper 95% Confidence Interval:	$D = 0.050 * DBH + 0.9076$
Upper 99% Confidence Interval:	$D = 0.050 * DBH + 1.1720$

All of the data collected pertaining to windthrow pit diameter are presented in Figure 21. These data were converted to equivalent circular diameter as previously discussed, except for the data from Achim and Nicoll (2009), as they determined that the lateral diameter alone characterized this data set since the shape of the root plates was very near that of a semi-circle.

Unfortunately, careful observations of the complete data set in Figure 21

Figure 21. All data collected regarding diameter of windthrow pits.



revealed that the data from Achim and Nicoll have significantly larger root plates than all of the other studies. Figure 22 clearly illustrates this issue. One possible explanation for the higher values is the fact that the Achim and Nicoll (2009) study focused on windthrow events that were primarily in peaty soils. It is well documented in the literature that peaty soils lead to larger root biomass and therefore larger windthrow pits due to the nature of peat (Štofko and Kodrík 2008; Crow 2005; Tobin et al. 2007). Peaty soils are typically very weak, retain water quite well, and are rich in nutrients. The poor soil strength may require trees to have larger root systems for stability, and the other factors provide trees with the essentials to grow oversized root systems. Additionally, in a storm-induced windthrow event, the loading is dynamic, and the soil is likely wet due to weather conditions. Both of these factors, as well as the fact that this data set was from winched-over trees, may result in Achim's and Nicoll's data being artificially high (Rudnicki 2012). Because the purpose of this study was to evaluate windthrow pits on and near levees (which do not usually contain peat), the Achim and Nicoll data set were not applied to this study.

All remaining windthrow pit diameter data are plotted in Figure 23. Data from Simon (2010), Peterson (2007), and Peterson (2000) are highlighted specifically, as these three data sets appear to account for the majority of the variability in the data. One reason that this may be is the large time delay between the blowdown event and measurement collection for each of these

data sets. Both studies by Peterson had a delay of two years between the blowdown event and the measurements. Likewise, the data points collected by Simon had time delays of 40 years for some of the pits sampled.

Figure 22. Comparison of Achim and Nicoll (2009) to other data.

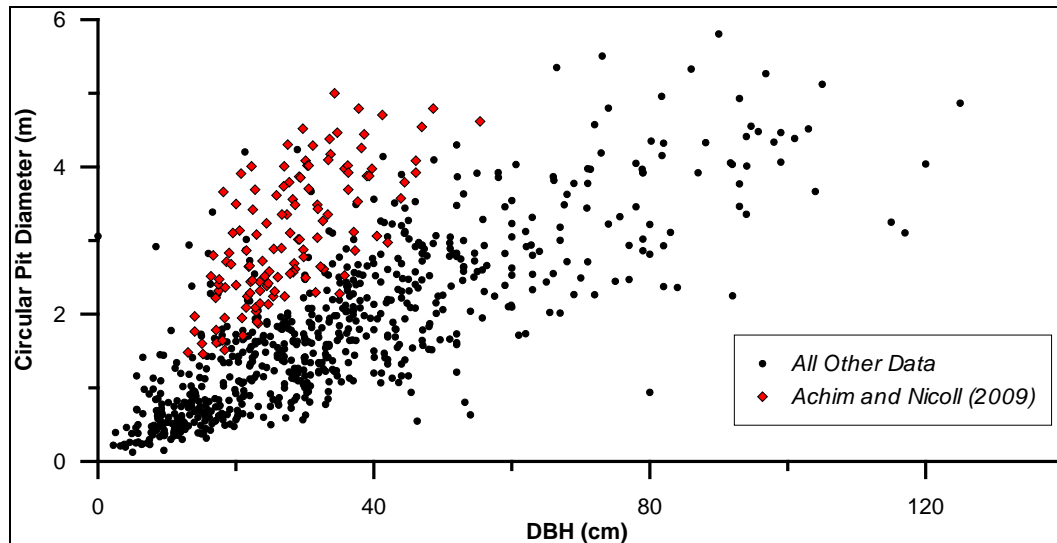
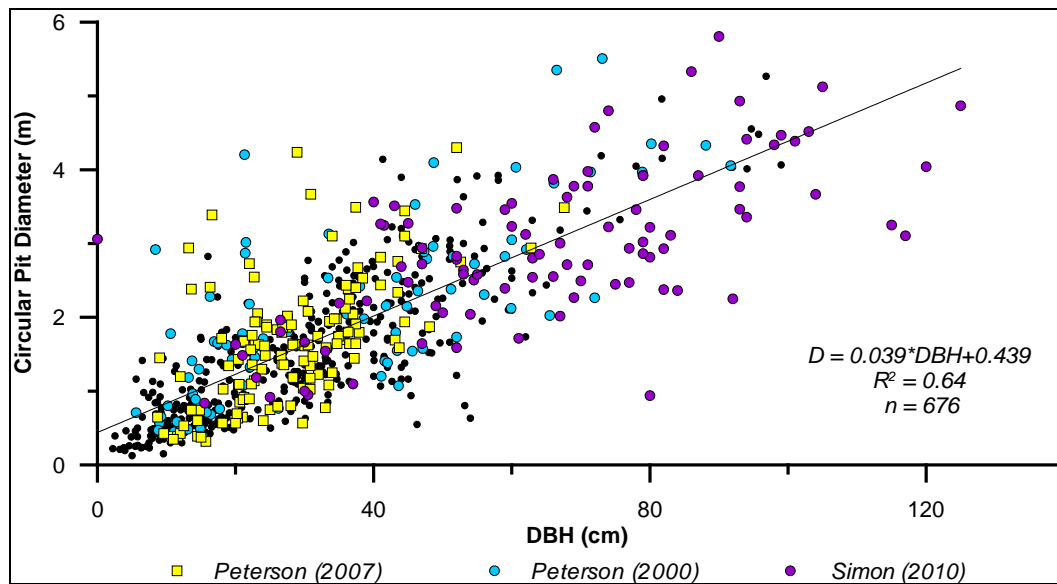


Figure 23. Windthrow pit diameter data excluding Achim and Nicoll (2009).



A linear regression of all data (except Achim and Nicoll) yields a correlation coefficient of 0.64 on 676 observations. The 95% confidence intervals for the linear regression are plotted in Figure 24. As can be seen, the confidence intervals include the majority of the windthrow pit observations. Therefore, it is reasonable to use the upper 95% confidence interval as a predictive

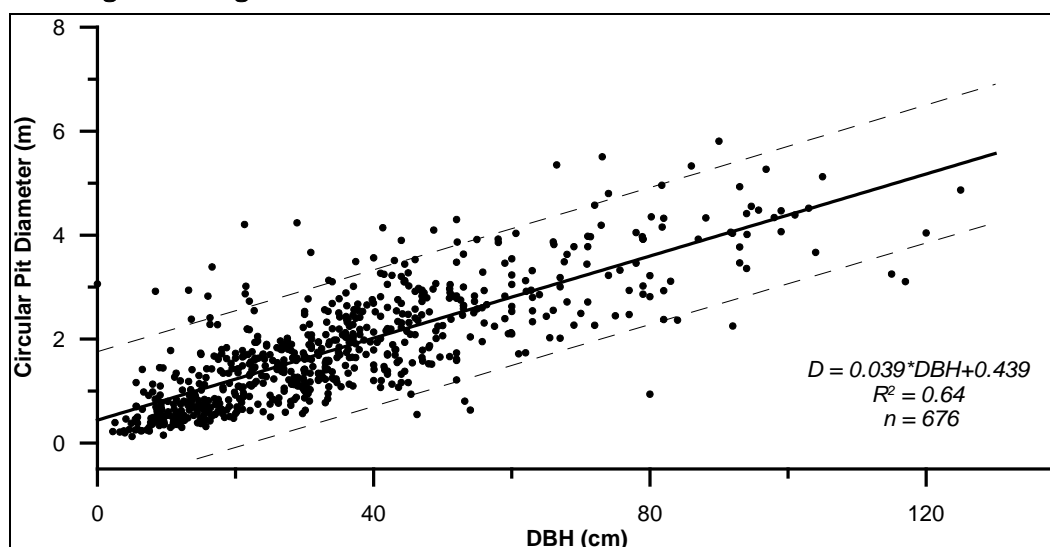
measure for evaluating the size of windthrow events. If a higher level of conservatism is desired, the upper 99% confidence interval may be used.

Table 17 presents the equations for the linear best-fit line and upper 95% and 99% confidence intervals.

Table 17. Regression equations for all 676 observations.

Mean:	$D = 0.039 * DBH + 0.439$
Upper 95% Confidence Interval:	$D = 0.039 * DBH + 1.751$
Upper 99% Confidence Interval:	$D = 0.039 * DBH + 2.164$

Figure 24. Regression of windthrow diameter data and 95% confidence intervals.



The previous data assessment was able to include all 676 observations obtained from the literature due to the concept of equivalent circular diameter. It is recognized that cases may arise where it is desirable to know the actual dimensions (length and width) of a tree windthrow pit. For this reason, the subset of data containing length and width measurements was assessed separately. Figure 25 and Figure 26 illustrate the relationships obtained for length and width from the 304 observations for which this information was reported.

Figure 25. Compilation of windthrow pit length data from Peterson et al. (1990), Clinton and Baker (2000), Peterson (2007), Simon (2010), and Kooch et al. (2012).

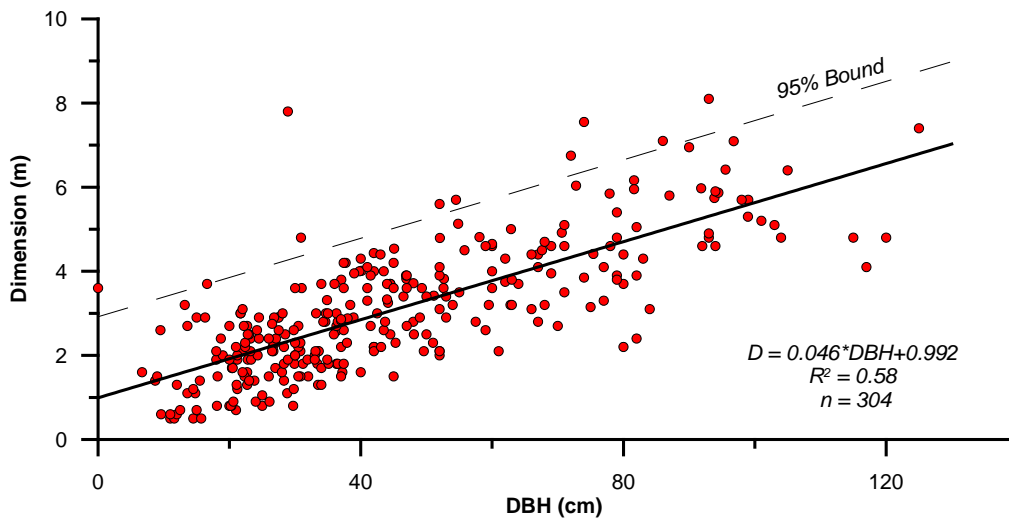
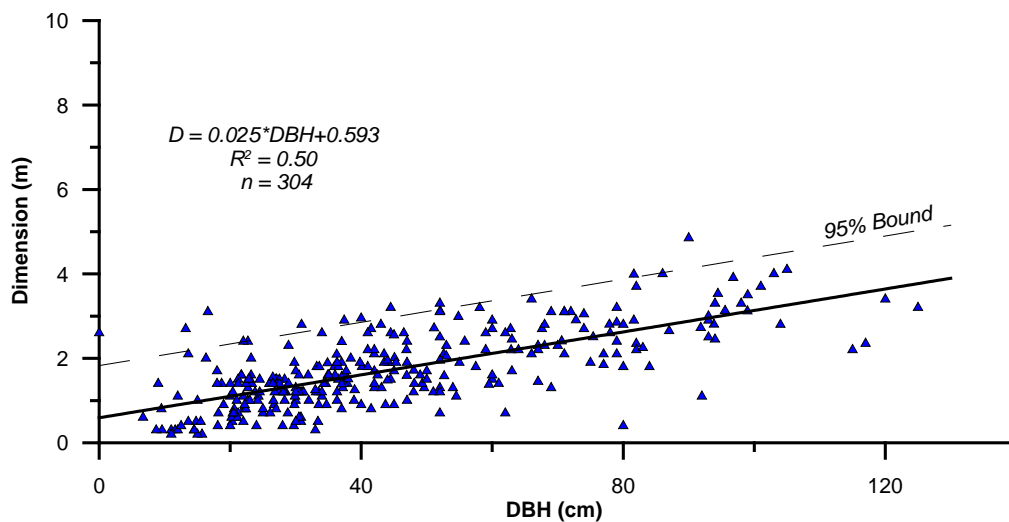


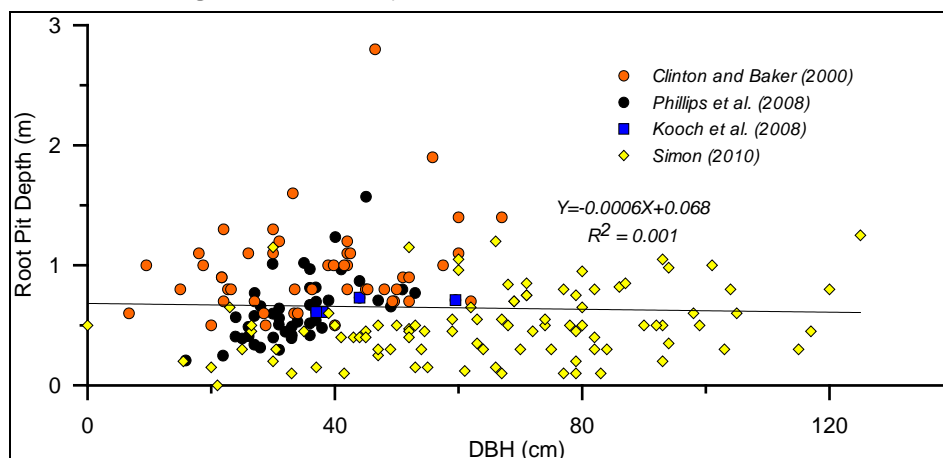
Figure 26. Compilation of windthrow pit width data from Peterson et al. (1990), Clinton and Baker (2000), Peterson (2007), Simon (2010), and Kooch et al. (2012).



5.2 Windthrow pit depth

Of all the studies previously mentioned, only Clinton and Baker (2000); Phillips et al. (2008); Simon (2010); and Kooch et al. (2012) reported data on the depths of the root pits. A summary plot of the pit depth data collected is provided in Figure 27. From this plot, it appears that a correlation does not exist between tree DBH and root-plate depth, as indicated by the coefficient of determination (R^2)'s being approximately equal to zero. However, this data set is a limited data set with the majority of data points from Simon (2010), which included data up to 40 years in age. Therefore, another attempt will be made to determine whether trends exist by assessing the volume data collected.

Figure 27. Summary plot of all pit depth data collected.



Gallaway et al. (2009); Lenart et al. (2010); and Phillips et al. (2008) all reported root-plate volume data. From the previous section, it is known that a strong relationship exists between tree diameter and root-plate diameter. Because a strong relationship exists between DBH and diameter, a strong relationship must also exist between DBH and root-plate area. Therefore, if a strong relationship had existed between DBH and root-plate depth, a relationship should also be exhibited between DBH and root-plate volume. This concept is illustrated graphically in Figure 28. As can be seen from Figure 29, a strong relationship between DBH and root-plate volume does not exist. This is due to the rooting depth's being influenced by numerous factors outside of mechanical stability. For instance, the depth to sufficient water will cause roots in some areas to be deeper than roots in others. Likewise, the soil characteristics and depth of topsoil in a region will influence the rooting depth (Phillips et al. 2008). Finally, it must be recognized that rooting depths are also greatly influenced by species (Crow 2005).

Despite the fact that a trend was not illustrated by the depth data or by the volume data as discussed above, general guidelines do exist in the literature regarding root-plate depth. The following discussion will provide an overview of these general guidelines and compare them to the limited data that are available regarding root depth in this study.

Coder (2010) suggested that the root-plate depth may be computed as a function of DBH. One such way is the Coder Root Plate Model in which the depth of the root plate (in feet) is obtained by multiplying the tree DBH (in inches) by 0.3 (Coder 2010). This rule is plotted in comparison to the limited data available in Figure 30. As can be seen, this rule of thumb envelopes the majority of data; however, there is no maximum limit on the root depth in this formula.

Figure 28. Conceptual Illustration: A strong correlation between DBH and Area (a) combined with a strong correlation between DBH and Depth (b) should yield a strong correlation between DBH and volume (c).

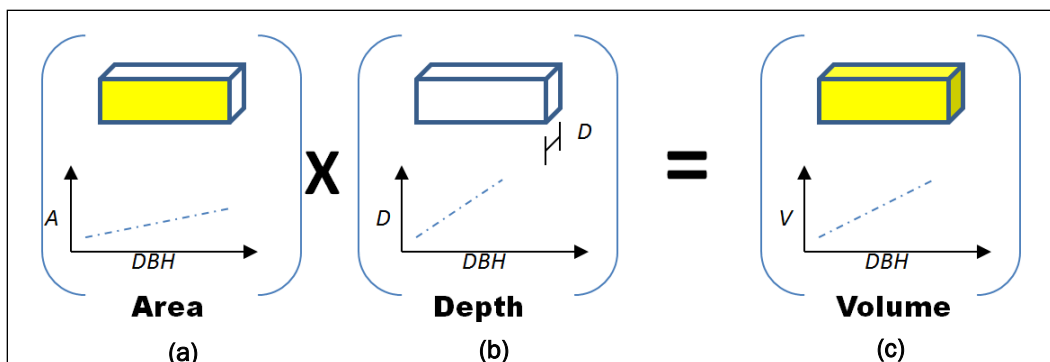


Figure 29. Root-plate volume as a function of DBH.

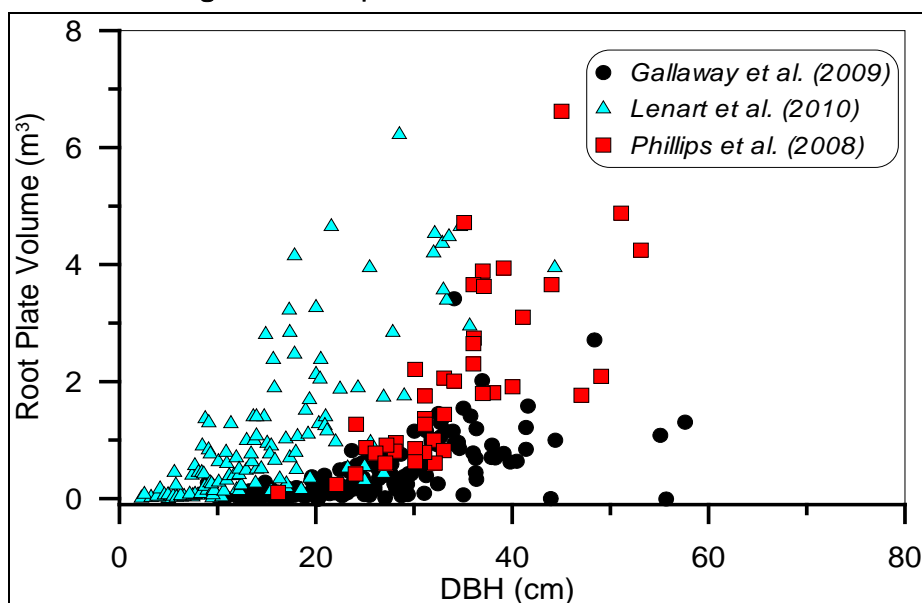
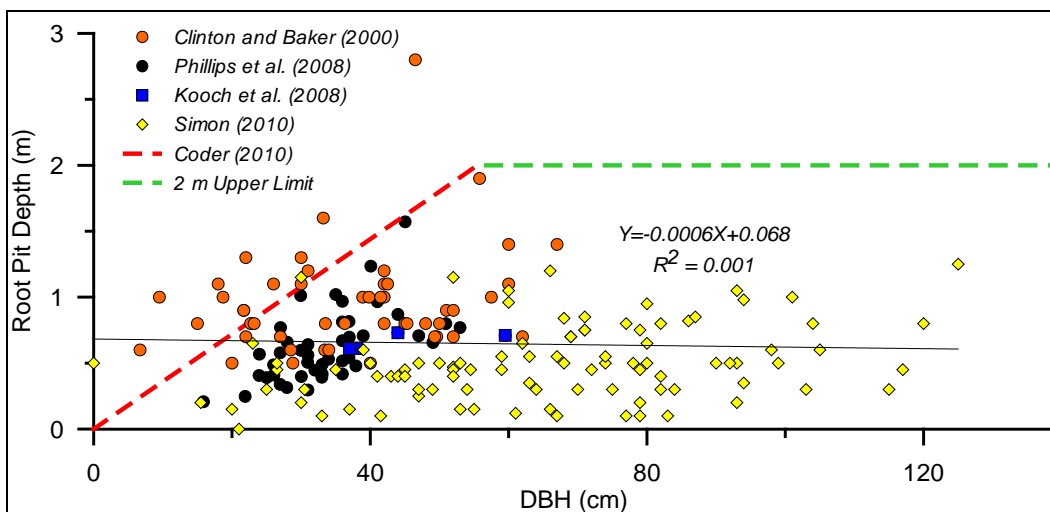


Figure 30. Root-plate depth as a function of tree DBH.



A maximum limit on the root-plate depth can be inferred from the observations made in the literature. Multiple authors have stated that the majority of tree roots are in the top 1 m of soil (Gilman 1990; Crow 2005; Gerhold and Johnson 2003; Achim and Nicoll 2009; Norman, Schaetzl, and Small 1995). In fact, Crow (2005) states that 90 to 99% of the root mass lies within the upper 1 m of soil. Cutler et al. (1990) surveyed thousands of windthrown trees throughout Great Britain during a 1990 windthrow event. Of the nearly 3,500 trees that were surveyed as part of this study, 46.5% of trees had root-plate depths less than 1 m, 50% had root-plate depths between 1 and 2 m, and 3.5% had root-plate depths greater than 2 m. Based on Cutler et al., it seems reasonable that 2 m forms an upper limit on the probable depth of a resulting windthrow pit. The 2-m limit, combined with the Coder Root Plate Model, results in the compound envelope for root depth shown in Figure 30. A close examination of this compound envelope reveals that it does indeed bound the majority of the data collected. Therefore, it seems to provide a rational means of estimating the resulting pit depth from a tree windthrow event.

6 Other Factors

This report presents a generalization of windthrow pit dimensions solely as a function of DBH. This was done because the goal of this report was to develop a simple, conservative method to estimate pit dimensions.

However, it must be recognized that numerous factors were shown to influence windthrow pit dimensions that may result in site-specific data that vary from the generalizations presented in this report. For instance, Achim and Nicoll found that soil type did influence the pit dimensions in their study to the extent that soil type alone was able to account for 12% of the variance beyond DBH as a primary variable. Additionally, Gallaway et al. (2009) stated that species, age, tree health, and soil moisture content also influence the pit dimensions. In general, the influence of these items is relatively small compared to the influence of DBH; however, it should be acknowledged that these additional factors can lead to pit dimensions that vary from the generalized trends presented in this report.

Finally, the slope of the terrain on which a tree is located has been found to have a significant influence on the pit dimensions. Gallaway et al. (2009) found that the ratio of the pit length to the pit width changes with increasing slope gradient. Furthermore, pit dimensions in general become larger with increasing slope gradient (Norman et al. 1995), resulting in a larger pit depth, pit length, and pit width on steep slopes.

Norman and associates (1995) surveyed 189 pit/mound pairs in northern Michigan for the sole purpose of assessing the influence of slope on soil transport by tree uprooting. From this study, it was found that the tree pit volume, length, and width all increase with increasing slope. However, the measurements were on tree pit/mound pairs that were estimated to be 100 to 150 years of age. The selection of old pit/mound pairs was made to account for the variation in dimensions that also results from age.

Unfortunately, this makes it difficult to determine if the trends observed were simply observations of weathering trends (i.e., more soil rolls back into the pit on flat ground versus steep ground) or actual variations in pit dimensions due to slope. Based on Gallaway et al. (2009), it is likely that the findings of Norman and associates attributing increases in size to increasing slope are correct. The regressions obtained by Norman's group are shown in Figures 31 and 32. The low coefficients of determination are

not surprising, as the tree DBH is not accounted for in these regressions. As previously shown, tree DBH is a primary dependent variable in predicting windthrow pit dimensions. Therefore, exclusion of DBH should result in poor correlations. Despite the poor correlation due to unaccounted variables, a clear trend of increasing dimensions with increasing slope is seen.

In evaluating the application of this increase in dimensions on sloped terrain, the authors considered scenarios that are likely to be encountered in levee environments. The slope of a levee will typically be less than a 1H:1V slope (100%). Looking at the increase in pit length from 1 to 100% in Figure 31, it can be seen that this range results in a maximum increase of 59%. The 95% confidence interval on equivalent circular pit diameters provided in Figure 24 is almost 400% larger than the mean value. Therefore, if the upper 95% confidence interval is used as a means of estimating the pit dimensions, it is the authors' opinion that adjusting for the increase due to slope is likely unnecessary due to the amount of conservatism incorporated in the initial estimate. If mean values are used as a means of estimating diameter, an adjustment may be appropriate.

Likewise, it is easily seen that the dimensions predicted from the pit depth regression in Figure 31 are all below 1 m in depth. As the upper limit on the suggested pit depth is 2 m, is it unlikely that it is necessary to adjust any pit depth dimensions to be larger than 2 m. However, it may be rational to increase the shallower depths predicted by the Coder Root Plate Model according to the results of Norman et al. (1995).

Figure 31. Pit length and depth regressions for 186 data points from Norman et al. (1995).

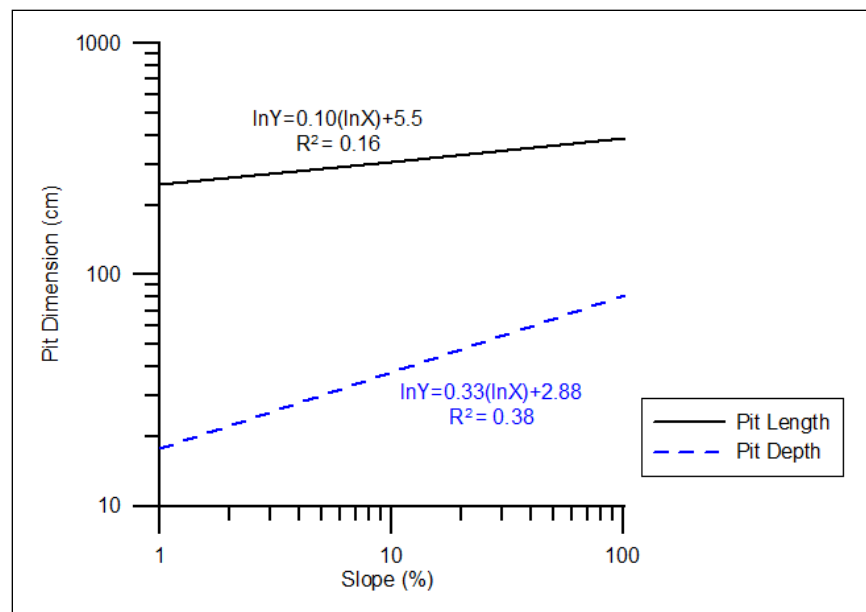
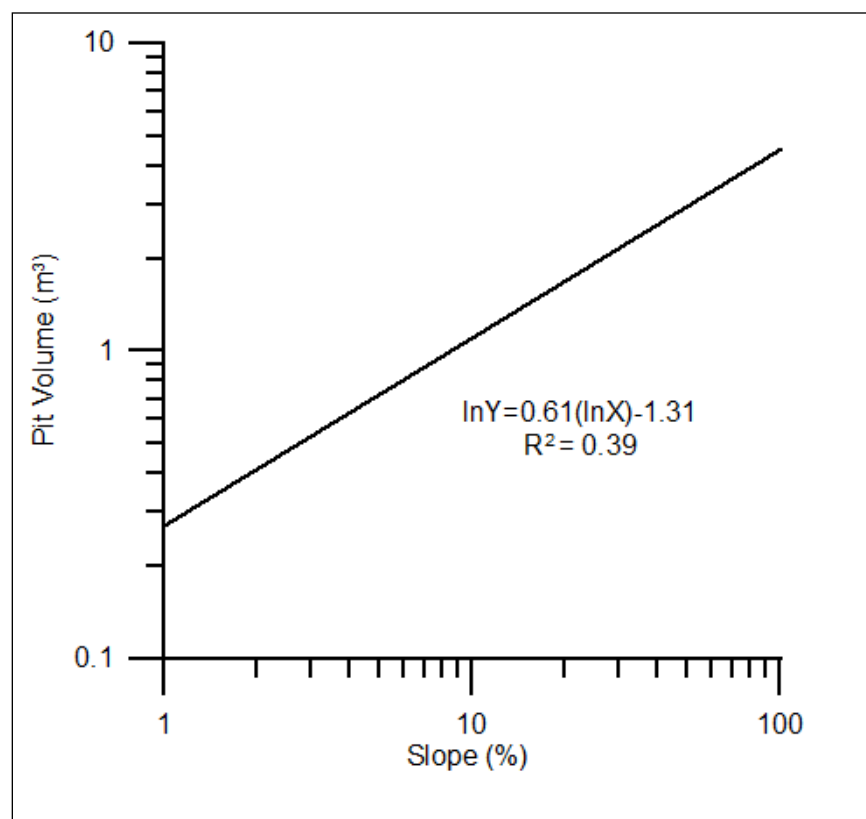


Figure 32. Pit volume versus slope regression for 186 data points (Norman et al. 1995).

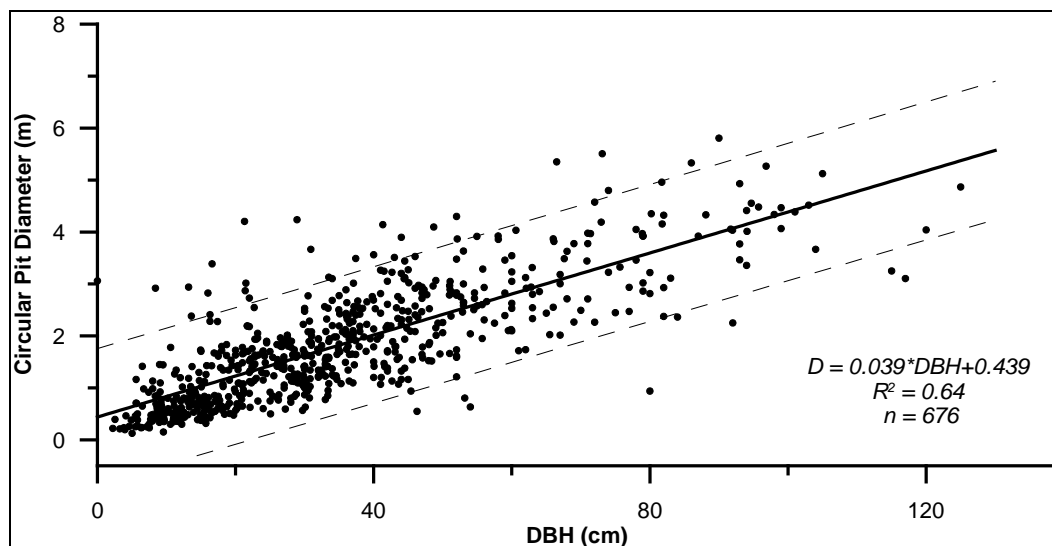


7 Summary

This study synthesizes existing literature regarding tree windthrow for the purpose of developing data from which the void dimensions of a windthrow pit can be estimated. This was accomplished by collecting data from existing scientific literature regarding windthrow events that were studied in the past. A review of historical studies in this area revealed that tree DBH was the single best independent variable for root regressions; therefore, only data for which pit dimensions could be obtained as a function of tree DBH were collected.

Overall, 12 previous studies were found from which significant data could be obtained. With regards to windthrow pit diameter, 676 useable data points were obtained, resulting in the regression shown in Figure 33. The linear regression fit the data well with DBH alone being able to account for 64% of the variation about the mean.

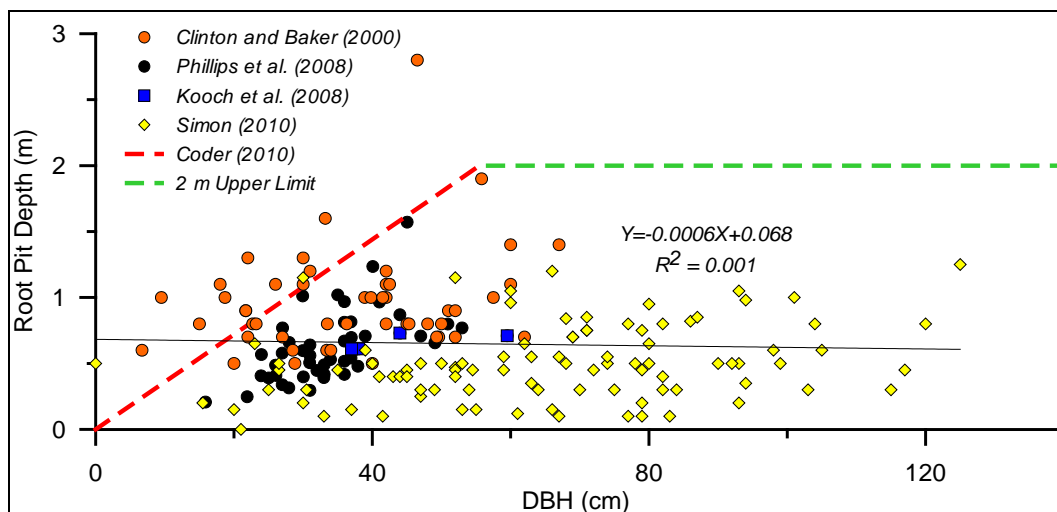
Figure 33. Windthrow pit diameter as a function of DBH: resulting data, regression, and 95% confidence intervals.



Windthrow pit depth exhibited significantly more variability than windthrow pit diameter. Only 197 data points were obtained from the literature describing windthrow pit depth as a function of DBH, and no correlation was found between DBH and pit depth measurements. Despite the limited data, generalized relationships were found in the literature that resulted in a compound envelope of all collected data. The primary relationship found in

the literature regarding root-plate depth was the Coder Root Plate Model (Coder 2010). This model is a simple equation that estimates the root-plate depth (in feet) as being equal to 0.3 times the DBH (in inches). This simple method of estimating root depth was found to bound the majority of the data collected in this study (Figure 34). Additionally, Cutler et al. (1990) found that only 3.5% of windthrow pits out of almost 3,500 trees had a root pit depth greater than 2 m. Therefore, a reasonable envelope of pit depth as a function of DBH is obtained by combining the Coder method with a maximum upper limit of 2 m in depth as shown in Figure 34.

Figure 34. Root-plate depth estimate.



Overall, this report developed a simple set of regressions that can be used to estimate the windthrow pit dimensions resulting from a tree windthrow event as a function of tree DBH.

8 Recommendations

As a result of synthesizing existing research regarding windthrow pit dimensions, this study developed a simple set of regressions that estimate the windthrow pit size as a function of tree DBH. The authors recommend that a tree windthrow pit be estimated as cylindrical in shape as shown in Figure 35 with the diameter and height taken as the pit diameter and pit depth, seen in Figure 36. Figure 36 provides a single figure that predicts the equivalent circular pit diameter from the 95% confidence interval shown in Figure 33 and the pit depth from the compound envelope shown in Figure 34. If a higher level of conservatism is desired, the 99% confidence interval may be used regarding the pit diameter. While it is recognized that most pit shapes are not cylindrical, the purpose of this study was to find a simple method that would encompass all scenarios. It is recognized that this will be overly conservative in many instances (e.g., where the root plate is conical). However, the authors felt that a cylindrical shape was the most appropriate for the purposes of this report.

Figure 35. Cylindrical representation of windthrow pit.

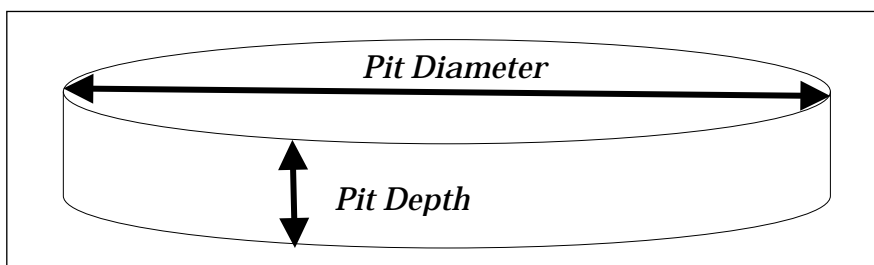
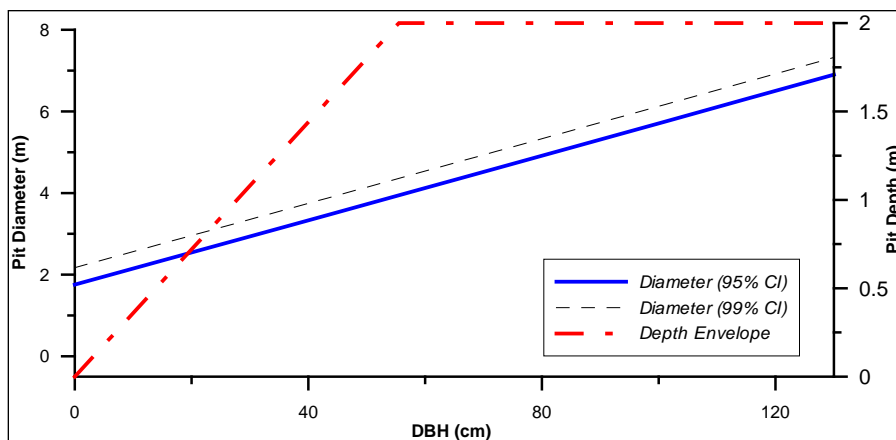


Figure 36. Recommended relationships for estimating windthrow pit dimensions.



While the relationships presented in Figure 36 provide a rational, scientific method for estimating windthrow pit dimensions, it should be recognized that these relationships were developed from limited data sets. As discussed in this study, various factors such as soil type, slope, and moisture conditions can have a significant impact on the pit dimensions. Specifically, it should be recognized that the relationship given for pit diameter is not suitable for use in peat soils, as this study clearly illustrated that peaty soils result in larger pit diameters. It should also be noted that windthrow pit dimensions increase with increasing slope as previously discussed. However, if the 95% confidence interval is used in making estimates of pit dimensions, it is unlikely that further increases in pit diameter are necessary, as the inherent conservatism in the 95% confidence interval more than accounts for the 50% increase in pit diameter that may be attributed to slope.

This report provides a means of estimating windthrow pit dimensions, but it does not comment on the relative significance of a void of this size on levee stability. Therefore, it is recommended that future research be conducted to determine if a void sized according to this study results in a significant reduction in a three-dimensional slope stability analysis. A void that is 2 m in depth will induce failure in some levees if analyzed in only two dimensions; however, this is not a two-dimensional problem, and future research should be conducted to assess the significance in three dimensions. Furthermore, analysis should be conducted to assess the influence voids may have at various slope positions. Additionally, future research could be conducted to increase the pit depth data set and provide a better estimation of depth.

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